A(40)Ar/(39) Ar study of oceanic and continental deformation processes during an oblique collision: Taconian orogeny in the Quebec reentrant of the Canadian Appalachians

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A ^{40}Ar/^{39}Ar study of oceanic and continental deformation processes during an oblique collision: Taconian orogeny in the Quebec reentrant of the Canadian Appalachians

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[1] Two phases of penetrative deformation are documented in the Taconian hinterland of the Appalachian orogen in the Gaspé Peninsula. D1 is associated with the obduction of the Mont-Albert ophiolite onto the Paleozoic Laurentian margin, whereas D2 corresponds to later transport of allochthons across the margin. In the metamorphic sole, S1 is a SE-dipping mylonitic fabric with a downdip lineation. In underlying metabasalts, D1 is characterized by NW-overturned and recumbent folds, and a subhorizontal S1 schistosity with an ENE-trending orogen-parallel lineation. D2 is characterized by a S2 steeply dipping penetrative axial-planar crenulation cleavage and NE-trending F2 folds. The intraoceanic thrusting of ophiolite is dated at 465 Ma (early D1) whereas emplacement of ophiolite and subsequent deformation of the margin was recorded by isotopic signatures between 459 and 456 Ma (late D1). D2 is dated at 448 Ma throughout the hinterland. Taconian transpressive deformation is related to an oblique collision within the Quebec reentrant of the Canadian Appalachians during the Ordovician. **Citation:** Malo, M., G. Ruffet, A. Pincivy, and A. Tremblay (2008), A ^{40}Ar/^{39}Ar study of oceanic and continental deformation processes during an oblique collision: Taconian orogeny in the Quebec reentrant of the Canadian Appalachians, *Tectonics*, *27*, TC4001, doi:10.1029/2006TC002094.

1. Introduction

[2] The eastern margin of the Laurentian craton is formed by promontories and reentrants (Figure 1) [*Thomas*, 1977]. The Gaspé Peninsula of the Canadian Appalachians is located in the innermost part of the Quebec reentrant, near the flank with the Newfoundland promontory. This particular geometry has influenced the tectonic evolution of the mountain belt during Paleozoic time [*Thomas*, 1977; *Stockmal et al.*, 1987; *Malo et al.*, 1995; *van Staal et al.*, 1998], particularly for the Ordovician Taconian orogeny with diachronous collisional events occurring later in the Quebec reentrant than on the Newfoundland promontory [*Stockmal et al.*, 1987; *Castonguay et al.*, 2001; *Pincivy et al.*, 2003]. In the Gaspé Peninsula, the geometry of the irregular Laurentian margin has also induced strike-slip deformation along major faults during the Devonian Acadian orogeny [*Malo et al.*, 1992; *Malo and Kirkwood*, 1995; *Kirkwood*, 1999; *Malo*, 2001; *Sacks et al.*, 2004]. Such strike-slip deformation could also have happened during the Ordovician Taconian orogeny because of the irregular geometry of the margin inherited from the Neoproterozoic Grenvillian basement [*Williams*, 1995]. On the other hand, the Taconian structural style in the Canadian Appalachians is traditionally associated with thrust tectonics and emplacement of allochthons onto the lower Paleozoic platform to the northwest, toward the Grenville Province [*Bird and Dewey*, 1970; *St-Julien and Hubert*, 1975; *Williams*, 1979; *Pinet and Tremblay*, 1995; *Cawood et al.*, 1995; *Waldron et al.*, 1998]. The geological map of the Gaspé Peninsula reflects this thrust tectonics style depicting distinct nappes of Cambrian and Ordovician rocks limited by large-scale NE-trending thrust faults [*Slivitzky et al.*, 1991]. Nevertheless, for the past 15 years, detailed structural analyses in the metamorphic domains of the Cambrian-Ordovician allochthons revealed a NE-trending orogen-parallel lineation [*St-Julien et al.*, 1990; *Camiré et al.*, 1993] and some indications of dextral shearing along one of the synmetamorphic large-scale ENE-trending faults, the Shickshock Sud fault [*Sacks et al.*, 2004]. These structural features are unusual in Cambrian-Ordovician rocks of the Gaspé Peninsula and elsewhere in the Canadian Appalachians and must be explained in terms of the Ordovician collisional history of the orogen. Preliminary geochronological data on regional metamorphism allowed to roughly estimate the timing of the deformation in the Taconian hinterland of the Gaspé Peninsula, as early Late Ordovician [*Lux*, 1986; *Pincivy*, 2003; *Pincivy et al.*, 2003]. In the present paper, we present a detailed geochronological and structural study, in and around the Taconian hinterland, which supports a new kinematic model for the early Paleozoic orogenic events in the Quebec reentrant. Our new data from the Gaspé Peninsula help to better define the timing and geodynamic setting of tectonic processes related to the closure of the Humber seaway [*Waldron and van Staal*, 2001; *van Staal*, 2005] of the Ordovician Iapetus Ocean. In the following, our use of "obduction" includes

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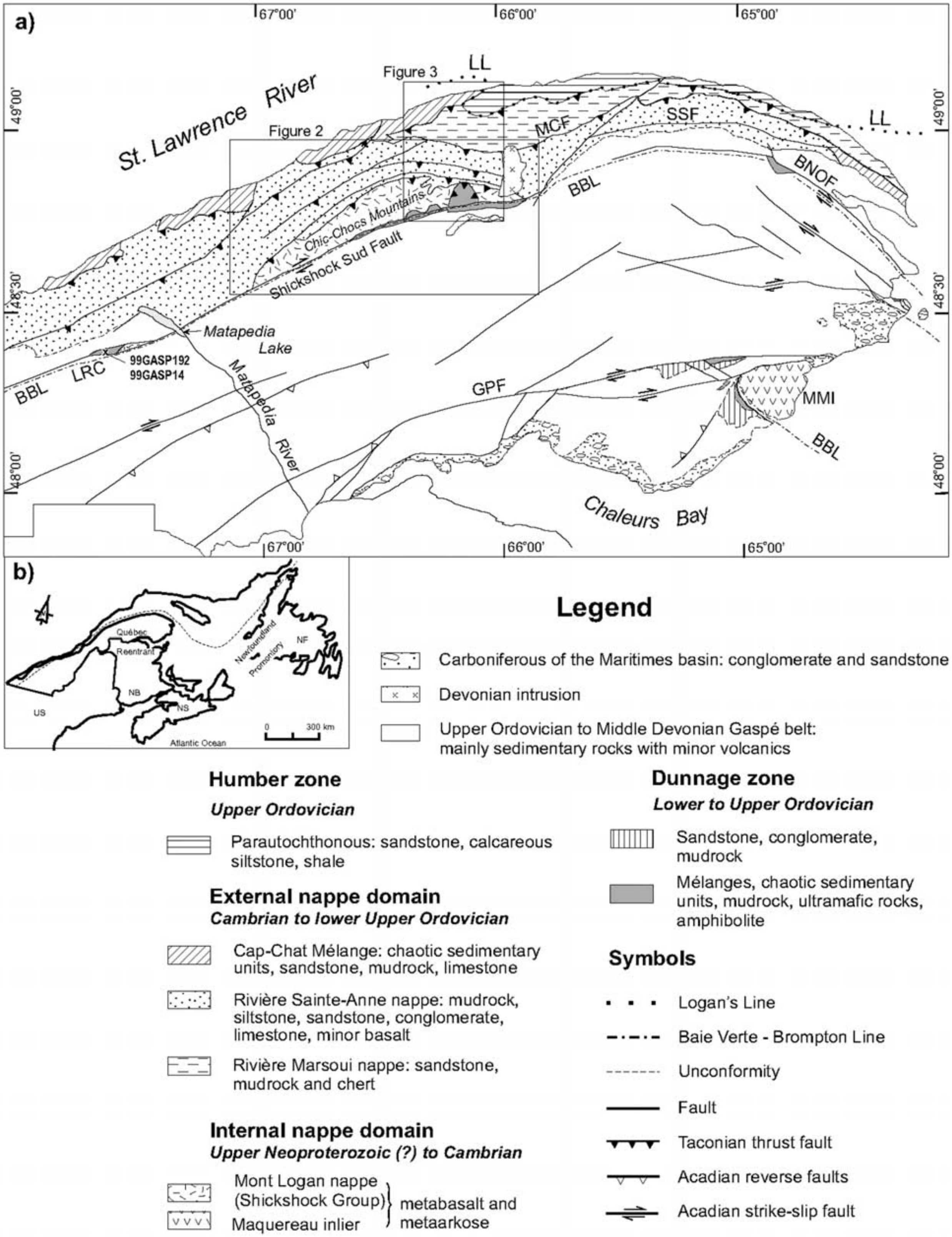

Figure 1. Gaspé Peninsula geology. BBL, Baie Verte-Brompton line; BNOF, Bras Nord-Ouest fault; MMI, Maquereau-Mictaw inlier; GPF, Grand Pabos fault; LL, Logan's Line; LRC, Lac Rédemption Complex; MCF, Méchins-Carcy fault; SSF, Shickshock Sud fault; NF, Newfoundland; 99GASP14 and 192, location of two samples from the LRC.

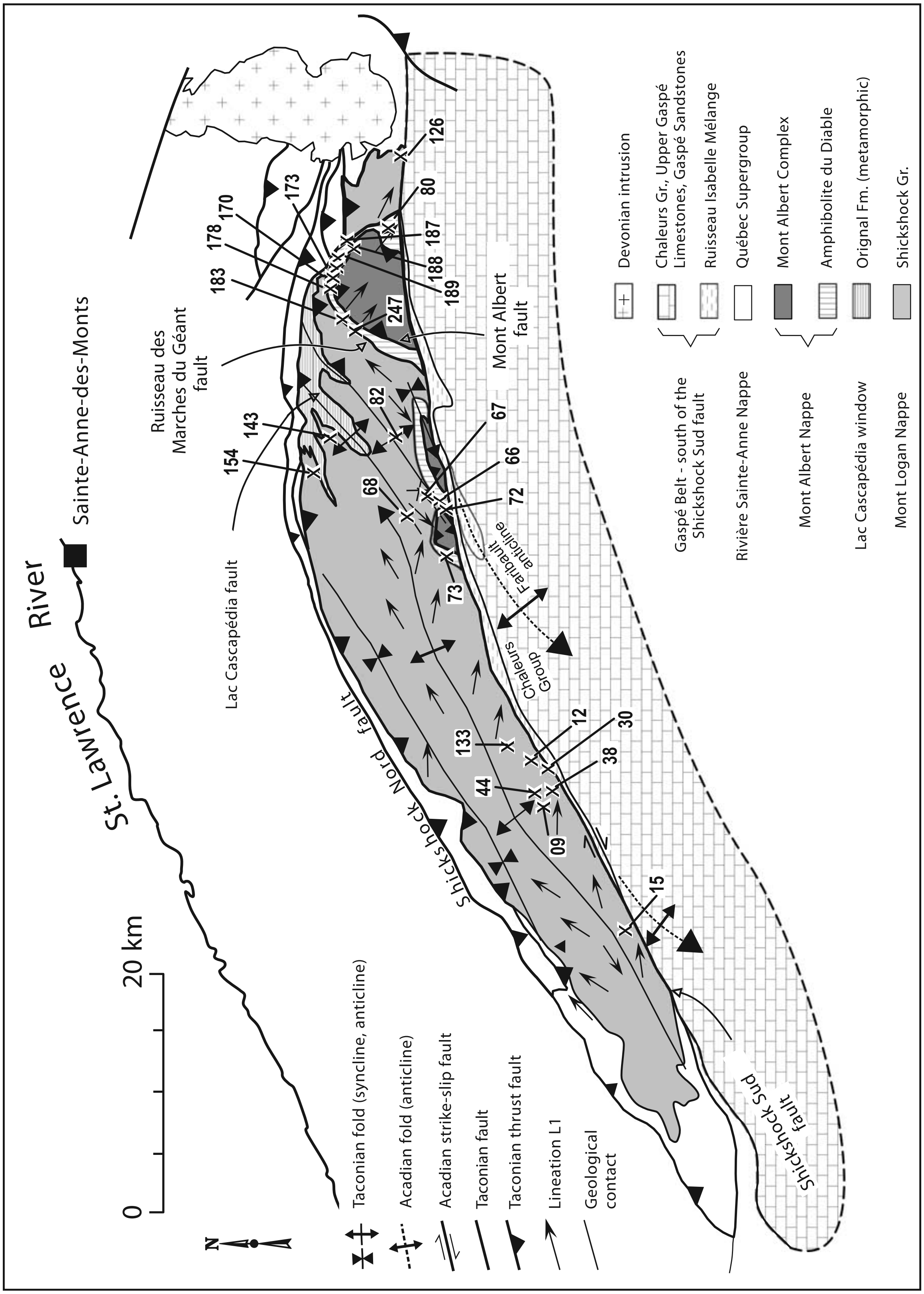

Figure 2. Geology of the hinterland and location of samples.

both early intraoceanic thrusting and structural thickening of the ophiolite nappe, and final emplacement onto the continental margin [*Gray et al.*, 2000].

2. Regional Geological Setting

[3] Three Paleozoic rock assemblages of the Canadian Appalachians constitute the Gaspé Peninsula [*Williams*, 1995] (Figure 1): (1) lower Paleozoic rocks of the ancient passive margin of Laurentia (Humber zone) and the adjacent oceanic domain of Iapetus Ocean (Dunnage zones); (2) middle Paleozoic rocks of the successor basin, the Gaspé Belt; and (3) Carboniferous rocks of the Maritimes Basin. The lower Paleozoic rocks were affected by both the Middle to Late Ordovician Taconian orogeny and the Middle to Late Devonian Acadian orogeny; the middle Paleozoic rocks have been mainly deformed by the Acadian orogeny, but they also contain structural features attributed to the Siluro-Devonian Salinic disturbance [*Malo*, 2001]; the lower, middle and upper Paleozoic rock assemblages were largely unaffected by the Late Pensylvanian–Permian Alleghanian orogeny.

[4] Rocks of the Humber zone, mainly located in the northern part of the peninsula but also in the Maquereau-Mictaw inlier to the south (Figure 1), represent rift-related basalts, slope and rise deposits. The Humber zone is bounded to the north by the Logan's Line, the western limit of allochthons, and to the south by the Baie Verte-Brompton Line (Figure 1) [*Williams and St-Julien*, 1982], the eastern limit with Dunnage zone rocks. The Dunnage zone is represented by inliers of Ordovician oceanic turbidites, mélanges and by ultramafic rock slices bounded by major faults, such as the Shickshock Sud, Bras-Nord-Ouest, Grand Pabos and Rivière Port-Daniel faults (Figure 1). These rock assemblages on the Laurentian side of the Iapetus Ocean belong to the Notre Dame subzone of the Dunnage zone [*Williams et al.*, 1988]. Rocks of the Gaspé Belt (Figure 1) consist of Upper Ordovician to Middle Devonian rocks made up of sedimentary rocks and minor amounts of mafic volcanic rocks. Unmetamorphosed flat-lying Carboniferous sandstones and conglomerates of the Maritimes Basin unconformably overly older rock units in the southern Gaspé Peninsula (Figure 1).

[5] The Taconian orogeny in the Gaspé Peninsula is related to ophiolite obduction, collision of continental magmatic arc terranes, and associated crustal thickening of the Laurentian margin during Middle to Late Ordovician time [*De Broucker*, 1987; *Slivitzky et al.*, 1991; *Pincivy et al.*, 2003]. At the scale of the Canadian Appalachians, these tectonic events might be related to the closure of the Humber seaway [*Waldron and van Staal*, 2001]. The Taconian orogeny is characterized in the external Humber zone (Taconian foreland) by NW-directed regional thrusts and stacking of thrust sheets (nappes) (Figure 1). The Taconian structural features in the Taconian hinterland are, however, more complex and will be discussed in this paper. The second major orogenic event in the Gaspé Peninsula is the Middle Devonian Acadian orogeny which resulted from oblique continental collision between peri-Gondwanan terranes and Laurentia with its Taconian accreted terranes [*Malo et al.*, 1995]. It is characterized in the Gaspé Belt by large, open and upright NE-trending folds, NW-directed high-angle reverse faults and dextral ENE- to E-trending strike-slip faults such as the Shickshock Sud and the Grand Pabos faults (Figure 1). Deformation features related to these two major strike-slip faults are compatible with a classical strike-slip tectonics model [*Malo and Béland*, 1989; *Sacks et al.*, 2004]. New seismic data in the Gaspé Belt suggest that transpressional Middle Devonian Acadian folding and faulting were preceded by an initial stage of shortening that produced tectonic structures typical of fold and thrust belt [*Beausoleil et al.*, 2002; *Kirkwood et al.*, 2004]. During the Late Silurian, a minor tectonic event known as the Salinic disturbance is marked by angular and/or erosional unconformities, synsedimentary faulting and extensional-related folding mainly recorded in northeastern Gaspé Peninsula [*Bourque*, 2001; *Malo*, 2001].

3. Lithostratigraphy in and Around the Taconian Hinterland of Northern Gaspé Peninsula

[6] The Taconian hinterland in the Gaspé Peninsula comprises four fault-bounded tectonostratigraphic domains. From south to north (Figure 2, after *Slivitzky et al.* [1991]), they are the ophiolitic nappe of the Mont Albert Complex and the ophiolite metamorphic sole of the Amphibolite du Diable from the Dunnage zone, and the Mont Logan nappe and the Lac Cascapédia window from the internal Humber zone.

[7] To the north, the Taconian hinterland is followed by the Rivière Sainte-Anne and Rivière Marsoui nappes, and the parautochthonous zone (Figure 1). The Ruisseau Isabelle Mélange is a lithostratigraphic unit caught up in the Shickshock Sud fault zone, the southern limit of the Taconian hinterland. Further south, rocks belong to the Gaspé Belt (Figures 1, 2, and 3).

[8] The Mont Albert Complex is made up of tectonized harzburgites, which form three bodies: the Mont Albert, Mont du Sud and Mont Paul klippes [*Beaudin*, 1980, 1984; *Slivitzky et al.*, 1991] (Figures 2 and 3). The largest klippe, the Mont Albert, is an ophiolite body composed of 85% harzburgite and 15% dunite [*Beaudin*, 1980, 1984].

[9] The Amphibolite du Diable is the metamorphic sole at the base of the three ophiolitic klippes. At the Mont Albert klippe, the amphibolite is bordered by the Mont Albert fault, at the upper contact with the peridotite, and the Ruisseau des Marches du Géant fault at the lower contact with the Mont Logan nappe [*Gagnon and Jamieson*, 1986; *Slivitzky et al.*, 1991] (Figure 3). It is there composed of four metamorphic slices (amphibolite metamorphic facies) separated by shear zones [*Gagnon and Jamieson*, 1986; *O'Beirne-Ryan et al.*, 1990]. At the contact with the Mont Albert Complex, rocks in slice 1 are composed of hornblende, garnet, clinopyroxene, ±plagioclase and epidote. The occurrence of coronas of hornblende and epidote around garnets (Figures 5a and 5b) and of hornblende replacement of clinopyroxene has been interpreted as evi-

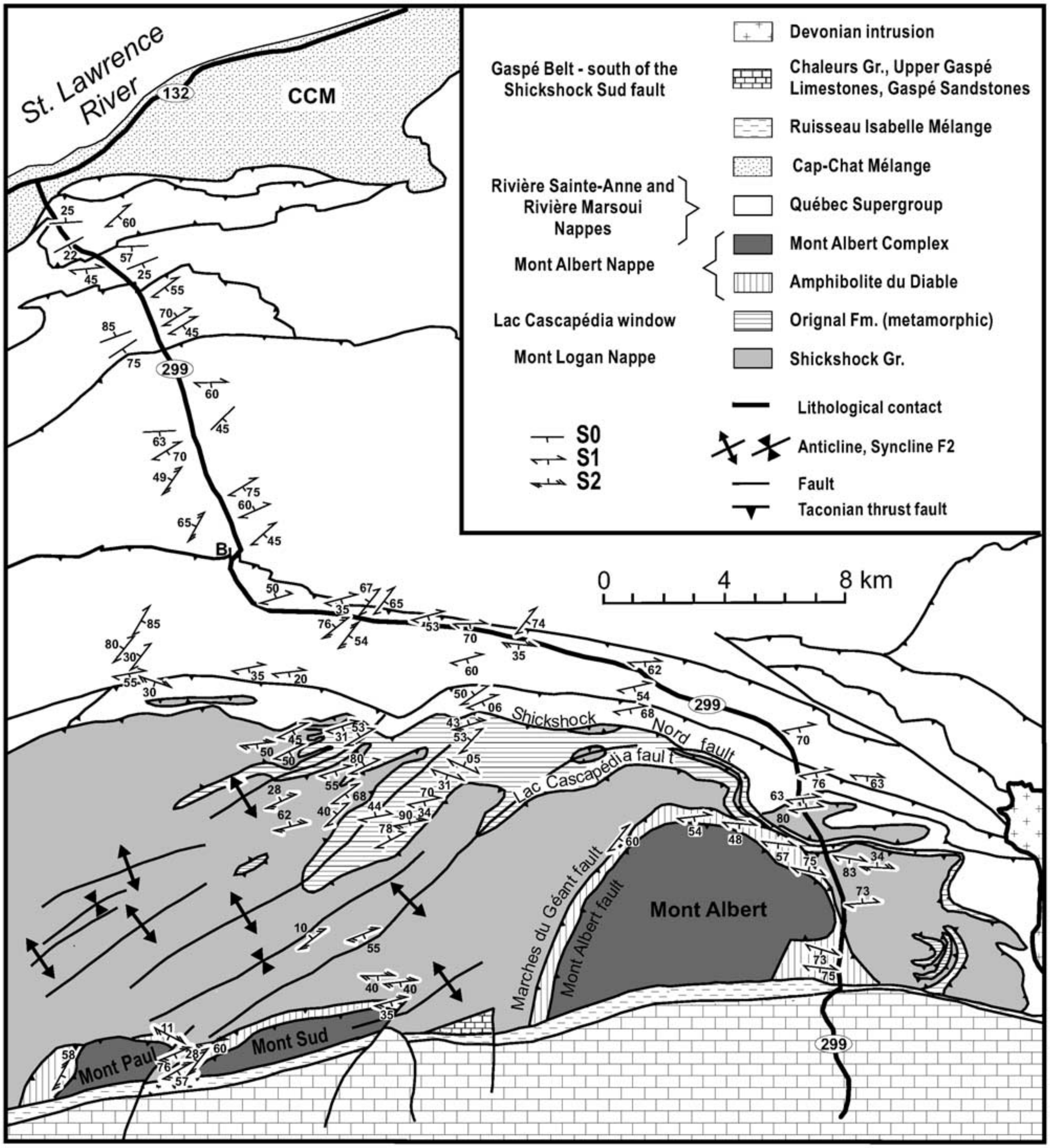

Figure 3. Geology of the study area along the road 299.

dence for retrogression from amphibolite facies to epidote-amphibolite facies [*O'Beirne-Ryan et al.*, 1990]. *Gagnon and Jamieson* [1986] interpret the mafic protolith as ancient oceanic ferrogabbros. Slice 2 underlying slice 1 is characterized by plagioclase-rich or epidote-rich rock layers with ±hornblende, clinopyroxene destabilized in hornblende, garnet destabilized in chlorite (Figure 5c) and quartz which could represent mixed ancient oceanic metaferrogabbros and quartzofeldspatic metasedimentary rocks [*Gagnon and Jamieson*, 1986; *O'Beirne-Ryan et al.*, 1990]. Rocks from slice 3 show a protomylonitic texture; they are composed of hornblende, epidote, plagioclase and quartz and are interpreted as interlayered metasediments and tholeiitic metabasalts. At the lower contact with the Mont Logan nappe, slice

4 consists of mylonitic tholeiitic basalts with hornblende, epidote, quartz and plagioclase. Small-scale veins of epidote that crosscut the mylonitic foliation suggest that the metamorphic sole was affected by retrogressive metamorphism [*Gagnon and Jamieson*, 1986; *O'Beirne-Ryan et al.*, 1990].

[10] The internal Humber zone consists of the Mont Logan nappe, the Lac Cascapédia window (Figures 1, 2, and 3) and the La Rédemption Complex (LRC, Figure 1). The Mont Logan nappe, which is composed essentially of the Neoproterozoic to Cambrian rocks of the Shickshock Group (Figure 4), is limited to the north by the Shickshock Nord fault (new name) and to the south by the Shickshock Sud fault (Figure 2). The Shickshock Group is made up of 85% of subalkaline to tholeiitic rift-related metabasalts [*Camiré et al.*, 1995] and 15% of metasedimentary rocks (mainly arkoses and minor conglomerates). The Lac Cascapédia window, located between the Lac Cascapédia and the Shickshock Nord faults, is composed of greenschist facies mudrocks with some intercalated siltstone beds, metamorphic rocks correlative with sedimentary rocks of the external Humber zone (Orignal Formation of the Quebec Supergroup, see below; Figure 4). Regional metamorphism varies from greenschist facies in the north to amphibolite facies in the south, just north of the Shickshock Sud fault [*Mattinson*, 1964; *St-Julien et al.*, 1990; *Camiré*, 1995].

[11] Rocks of the La Rédemption Complex occur as an inlier of Cambrian-Ordovician rocks west of the Mont Logan nappe (Figure 1) and are correlative with those of the Shickshock Group [*Sacks et al.*, 2004]. They consist of ultramafic rocks in the western part of the complex, and metasedimentary and metavolcanic rocks in the eastern part. Ultramafic rocks consist of harzburgite, serpentinite, and minor gabbros. Metasedimentary rocks consist of mudrock, arkosic sandstone, greywacke and metabasalt. These rocks are all metamorphosed at amphibolite grade. Mylonitic textures are found in amphibolitic rocks of the La Rédemption Complex close to the Shickshock Sud fault.

[12] The external Humber zone occurs between the Shickshock Nord fault and Logan's Line which represents the northern limit of allochthons (Figure 1) [*Slivitzky et al.*, 1991]. It comprises: (1) the Rivière Sainte-Anne nappe (Cambrian-Ordovician rocks of the Quebec Supergroup, mainly sandy, muddy, and calcareous turbidite successions, and minor volcanics), (2) the Rivière Marsoui nappe (lower Upper Ordovician, chert, shale, and muddy flysch of the Des Landes Formation), and (3) the Upper Ordovician Cap-Chat Mélange (Figures 1, 3, and 4). These rocks were affected by low-grade to anchi-metamorphism (prehnite-pumpellyite grade). Volcanic rocks of the Rivière Sainte-Anne nappe are transitional to alkaline basalts [*Camiré et al.*, 1995] which were dated between 565 to 556 Ma by U/Pb on zircons [*Cox and Hodych*, 2007]. The parautochthonous zone consists of the Upper Ordovician flysch succession represented by the Cloridorme Formation (Figures 1 and 4).

[13] The Ruisseau Isabelle Mélange, at the southern border of the Mont Logan Nappe (Figure 2), is composed of Ordovician sedimentary rock assemblages (Lower Ordovician Composite Shale, Upper Ordovician Black Shale, and Middle Ordovician Chromite-Bearing Sandstone assemblages), a Cambrian exotic block, an Ordovician Pebbly Mudstone assemblage and slivers of Ordovician serpentinized peridotite, and Cambrian metamorphic tectonites (Figure 4) [*Malo et al.*, 2001]. These various units are all in fault contact with each other. The Ruisseau Isabelle Mélange is interpreted as a tectonic mélange which was formed during several episodes of faulting between Late Ordovician and Middle Devonian times [*Malo et al.*, 2001].

[14] The Chaleurs Group is the lithostratigraphic unit of the Gaspé Belt directly south of the Shickshock Sud fault (Figure 2). It is made up of Silurian-lowermost Devonian shallow- to deep-water shelf, mixed carbonate and siliciclastic facies. The contact with older rocks is mainly faulted but Silurian rocks locally unconformably overlie the Composite Shale Assemblage of the Ruisseau Isabelle Mélange [*Malo et al.*, 2001]. The Gaspé Belt rocks were only affected by regional anchi- to low-grade metamorphism [*Hesse and Dalton*, 1991].

4. Structural Geology

[15] We present here structural data gathered along a north-south transect, where the relationships between external and internal Humber zones, the amphibolitic sole and the peridotite complex of the Dunnage zone are well-exposed (Figure 3).

4.1. Mont Albert Complex

[16] The deformational history of the Mont Albert Complex is characterized by pre-, syn- and post-obduction structures [*Beaudin*, 1980, 1984]. The first phase of deformation in the peridotite is a primary foliation defined by olivine and orthopyroxene which is considered as a mantle

Figure 4. Lithostratigraphic chart of northern Gaspé Appalachians. A, Acadian orogeny; Am, amphibolite metamorphic facies; DL, Des Landes Formation; ET, early Taconian; Gr, greenschist metamorphic facies; GS, Gaspé Sandstones Group; L, lower Cloridorme; LCF, Lac Cascapédia fault; LCW, Lac Cascapédia window; Ll, Llanvirnian; LT, late Taconian; MAF, Mont Albert fault; MCF, Méchins-Carcy fault; MT, middle Taconian; Or, Orignal Formation; RMGF, Ruisseau des Marches du Géant fault; RO, Rivière Ouelle Formation; S, Salinic disturbance; SSNF, Shickshock Nord fault; Sgr, Supergroup; T, Taconian orogeny; TAB, transitional to alkaline basalt; TO, Tourelle Formation; UGL, Upper Gaspé Limestones Group; und, undivided; YD, younging direction of metamorphism and D1 deformation in the hinterland. Radiometric age data come from *Tucker et al.* [1990], A. Grant (Geologic time scale, 1999, Prospectors and Developers Association of Canada, http://www.northernminer.com/Tools/timescl.pdf) and *Webby et al.* [2004].

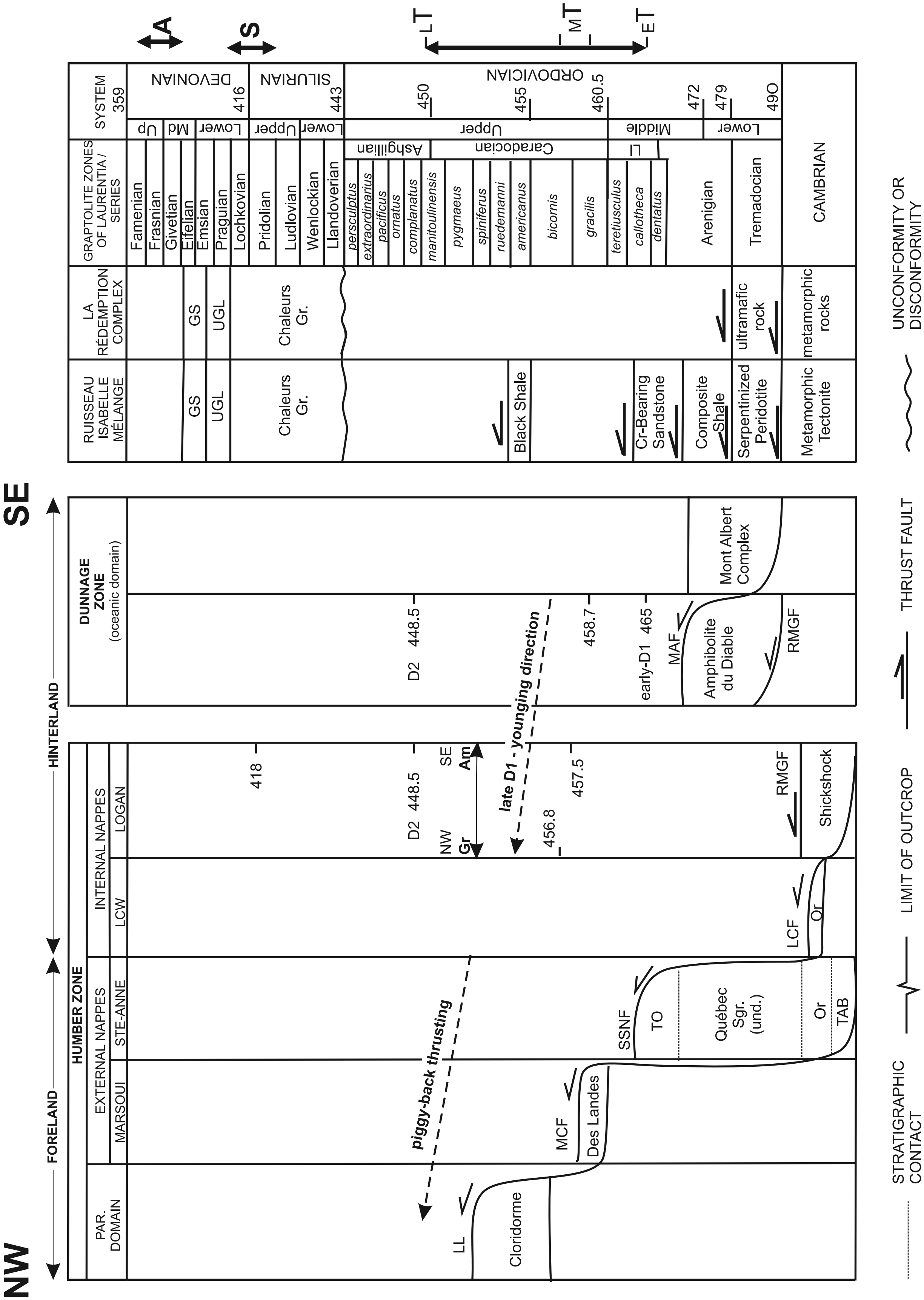
NW
SE
FORELAND
HINTERLAND
HUMBER ZONE
DUNNAGE ZONE (oceanic domain)
PAR. DOMAIN
EXTERNAL NAPPES
INTERNAL NAPPES
MARSOUI
STE-ANNE
LCW
LOGAN
Cloridorme
LL
MCF
Des Landes
SSNF
TO
Québec Sgr. (und.)
Or
TAB
LCF
RMGF
Shickshock
piggy-back thrusting
late D1 - younging direction
418
D2 448.5
NW Gr
SE Am
456.8
457.5
458.7
early-D1 465
MAF
Amphibolite du Diable
Mont Albert Complex
RUISSEAU ISABELLE MÉLANGE
LA RÉDEMPTION COMPLEX
GRAPTOLITE ZONES OF LAURENTIA / SERIES
SYSTEM
GS
UGL
Chaleurs Gr.
Black Shale
Cr-Bearing Sandstone
Composite Shale
Serpentinized Peridotite
Metamorphic Tectonite
ultramafic rock
metamorphic rocks
Famenian
Frasnian
Givetian
Eifelian
Emsian
Praguian
Lochkovian
Pridolian
Ludlovian
Wenlockian
Llandoverian
persculptus
extraordinarius
pacificus
ornatus
complanatus
manitoulinensis
pygmaeus
spiniferus
ruedemanni
americanus
bicornis
gracilis
teretiusculus
callotheca
dentatus
Arenigian
Tremadocian
CAMBRIAN
Ashgillian
Caradocian
Ll
Up
Md
Lower
Upper
Lower
Upper
Middle
Lower
DEVONIAN
SILURIAN
ORDOVICIAN
359
416
443
450
455
460.5
472
479
490
A
S
LT
MT
ET
STRATIGRAPHIC CONTACT
LIMIT OF OUTCROP
THRUST FAULT
UNCONFORMITY OR DISCONFORMITY

Figure 4

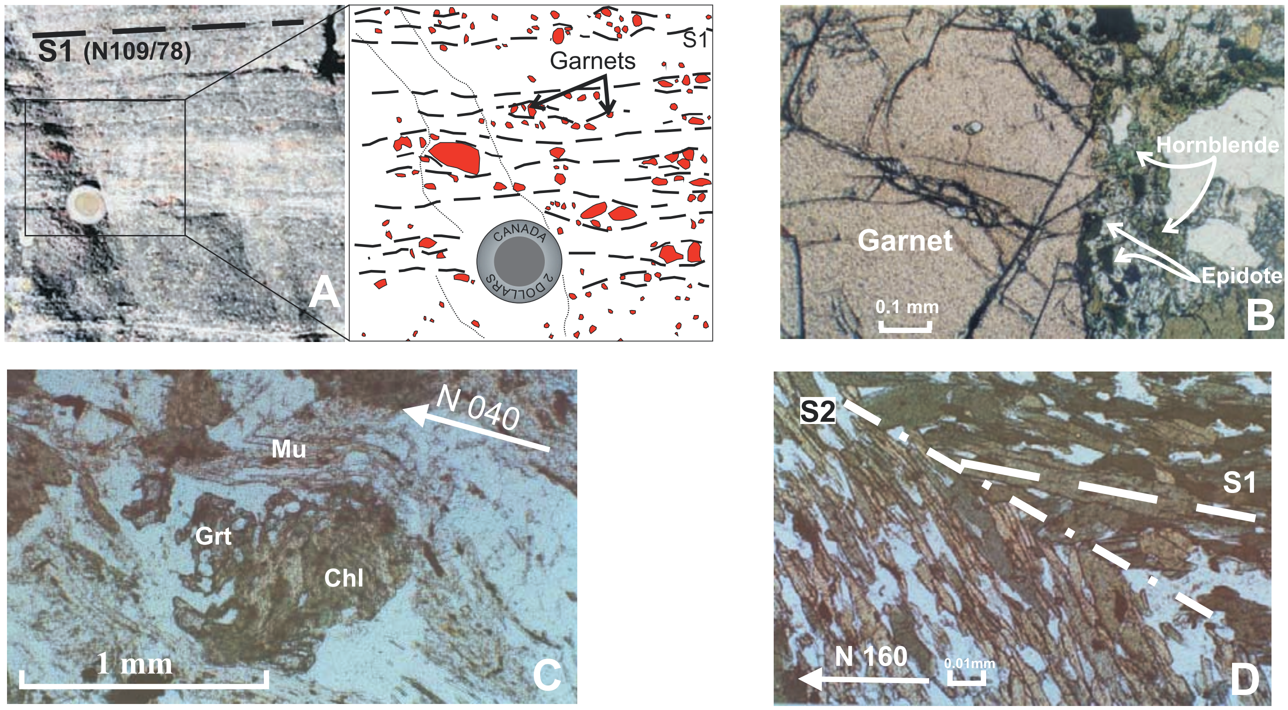

Figure 5. (a) Amphibolite facies with garnet in the Amphibolite du Diable. (b) Microphotograph of ring of hornblende and epidote around garnet in the amphibolite facies of the Amphibolite du Diable. (c) Microphotograph of garnet retromorphozed in chlorite in the Amphibolite du Diable. (d) Microphotograph of crenulated amphibolite of the Mont Sud metamorphic sole composed of hornblende, epidote, plagioclase, quartz, and opaque. There is no recrystallization of hornblende on crenulation cleavage planes S2.

fabric formed prior to obduction. This foliation is affected by a large-scale reclined fold that plunges moderately to the SW, which *Beaudin* [1980, 1984] believed to be coeval with the intraoceanic obduction. As these deformation features are restricted to the peridotite and not recognized in the Mont Logan nappe and in the Amphibolite du Diable, they are interpreted to have occurred within the Iapetus oceanic domain before the Taconian deformation of the Laurentian margin [*Beaudin*, 1984]. The Mont Albert Complex is truncated on its southern side by the Shickshock Sud fault, which dips steeply to the SE and is clearly a postobduction structure.

4.2. Amphibolite du Diable

[17] The metamorphic sole of the peridotite is characterized by a strong S1 mylonitic fabric (Figure 5a).This fabric dips moderately to the SE in the northeastern part of the Amphibolite du Diable at Mont Albert (Figure 6a) and is associated with a downdip L1 mineral lineation (Figure 6b) underlined by amphiboles and white micas. Shear-sense indicators (shear bands, asymmetric porphyroblasts and asymmetric folds, garnet rotation (Figure 5c) [see also *Sacks et al.*, 2004]) associated with this mineral lineation suggest NW-directed thrusting of the Mont Albert Complex and its metamorphic sole onto the Mont Logan nappe. The mylonitic fabric S1, underlined by hornblende crystals, resulted from the succession of tectonic processes during this "obduction" [*Gray et al.*, 2000]. Retrogression of the metamorphic assemblage (Figures 5a and 5c) occurred during the emplacement of the ophiolite and its metamorphic sole onto the continental Laurentian margin [*O'Beirne-Ryan et al.*, 1990; *Pincivy et al.*, 2003] (D1, Figure 4). The main fabric S1 of the metamorphic sole at the Mont Paul and Mont Sud is affected by a NE-trending S2 crenulation cleavage dipping to the SE (Figures 6c and 6d). In these two regions, S2 does not seem associated with any apparent metamorphic paragenesis (Figure 5d) [*Pincivy et al.*, 2003]. The metamorphic sole of the Mont Paul is folded around the peridotites (Figure 3) and the distribution of the poles to the main fabric S1 on a great circle reflects this folding (Figure 6c). The β pole to the main fabric indicates that F2 fold axes plunge gently to the SSW (Figure 6c).

4.3. Internal Humber Zone (Mont Logan Nappe and Lac Cascapédia Window)

[18] Two phases of penetrative deformation are documented in the Mont Logan nappe [*St-Julien et al.*, 1990; *Slivitzky et al.*, 1991] (Figure 4). The first phase of deformation (D1, Figure 4) is associated with the NW-directed overthrusting of the Mont Albert Complex onto the Mont

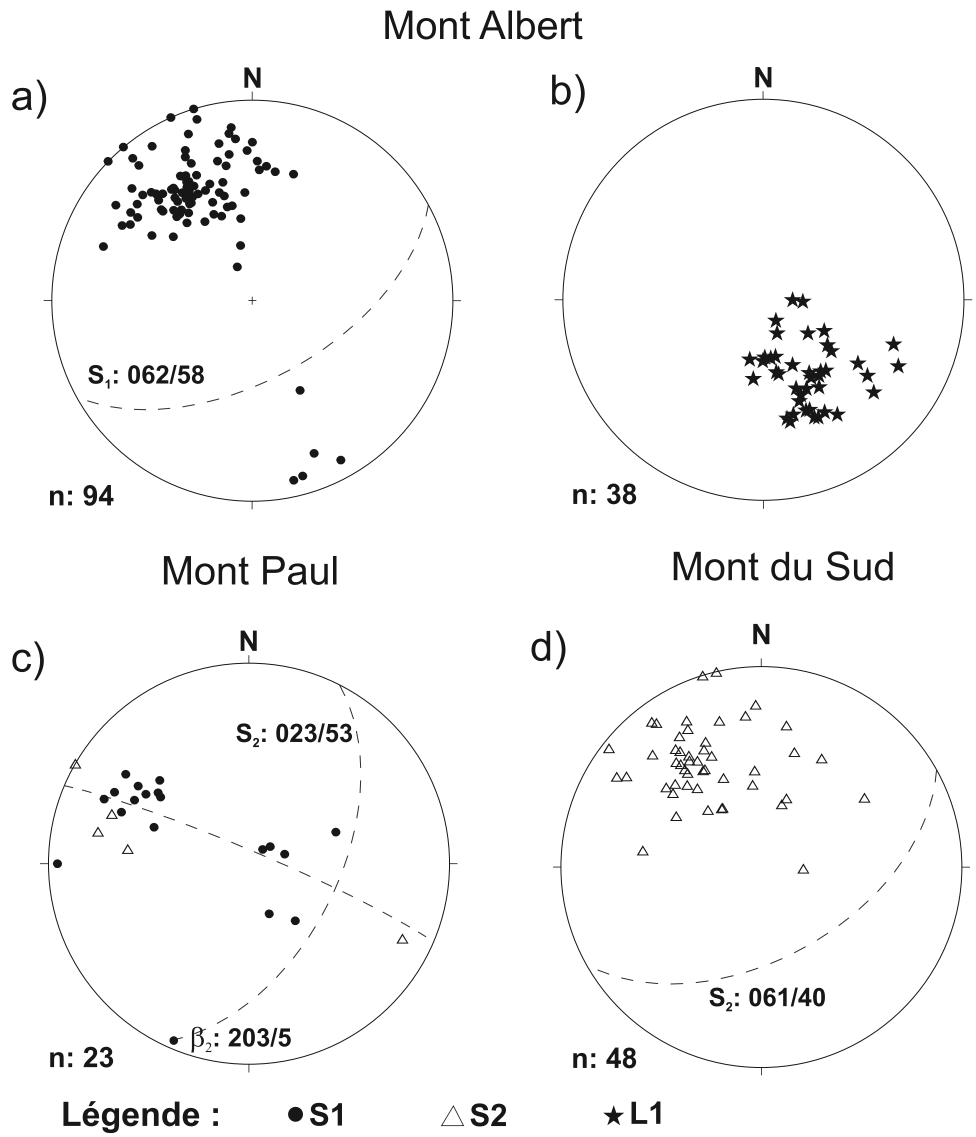

Figure 6. Stereoplots of structural data from the Amphibolite du Diable. (a) S1 at Mont Albert. (b) L1 at Mont Albert. (c) S1 and S2 at Mont Paul. (d) S2 at Mont du Sud.

Logan nappe [*St-Julien et al.*, 1990; *Slivitzky et al.*, 1991; *Camiré*, 1995]. D1 is characterized by NW-overturned and recumbent folds [*Mattinson*, 1964; *St-Julien et al.*, 1990; *Slivitzky et al.*, 1991], and by a subhorizontal metamorphic fabric (S1) formed at the greenschist to amphibolite facies (from north to south). This fabric trends ENE and dips gently to WNW or ESE within the Mont Logan nappe (Figure 7a) and Lac Cascapédia window (Figure 7c). Several poles of S1 clustered in the center of the stereonets indicate subhorizontal S1 (Figures 7a and 7c). Small-scale isoclinal folds with S1 as an axial-planar schistosity are observed locally (Figure 8a). A well-developed mineral and stretching lineation L1 [*Mattinson*, 1964; *Beaudin*, 1984; *St-Julien et al.*, 1990; *Slivitzky et al.*, 1991; *Camiré*, 1995, *Pincivy et al.*, 2003] is defined by the long axes of hornblende and epidote (Figure 8b), by quartz ribbon, stretched clasts in conglomerate (Figure 8c), and boudinaged quartz ribbons. L1 plunges gently to the ENE or WSW in the internal Humber zone (Figure 9).

[19] Rocks of the Shickshock Group are truncated by the Shickshock Sud fault at the southern boundary of the Mont Logan nappe. Structural and metamorphic analyses of the footwall and the hanging wall of the Shickshock Sud fault underline two distinct deformation events: (1) an early event recorded by high-temperature and ductile deformation features is only present in the Shickshock Group rocks of the footwall, and (2) a late dextral strike-slip motion is recorded on both sides of the fault [*Sacks et al.*, 2004]. In the footwall, mylonitic textures and kinematic indicators in the metamorphic rocks (amphibolite metamorphic grade) indicate an early high-temperature deformational event made of oblique thrusting (dextral and to the NW) which

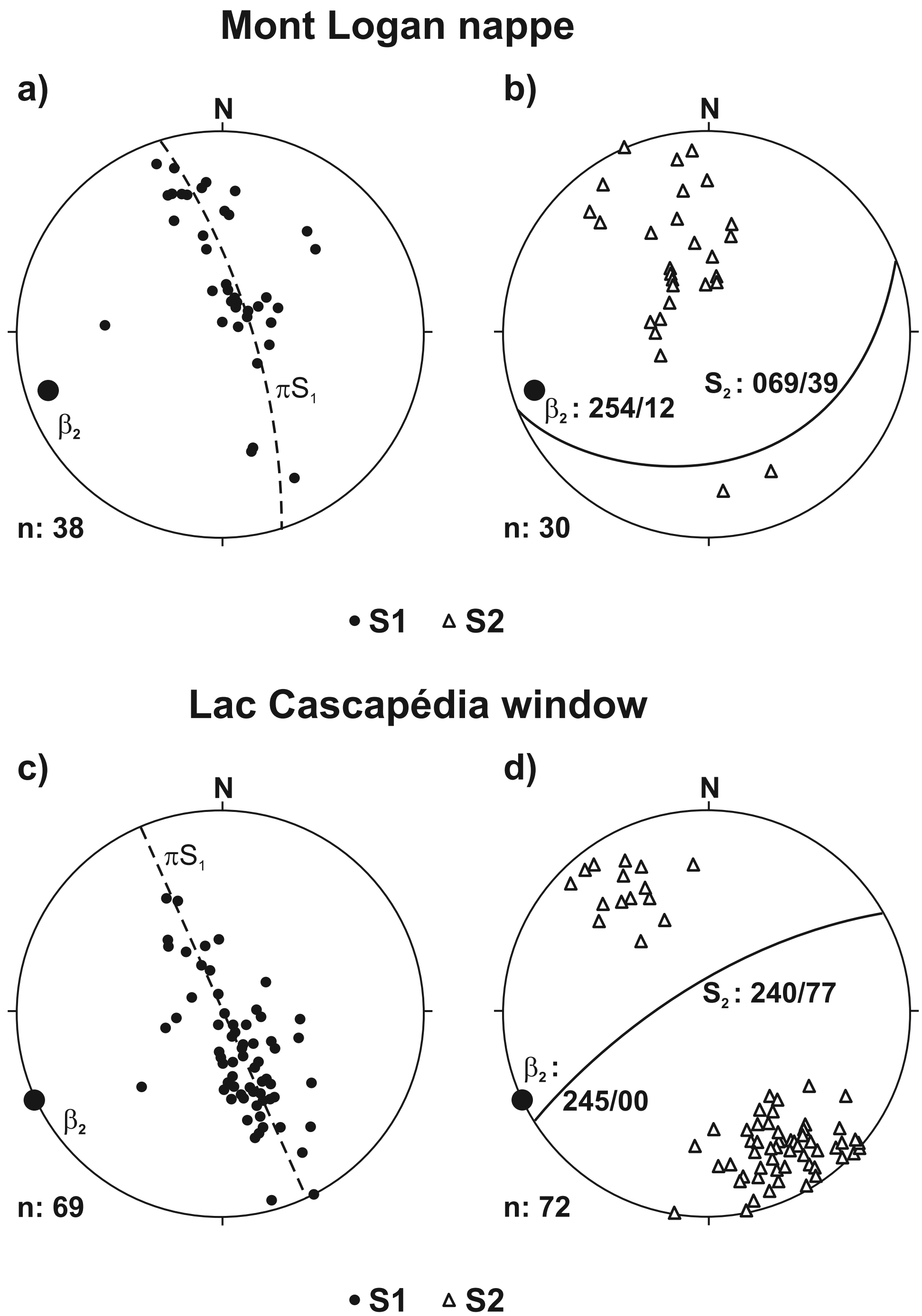

Figure 7. Stereoplots of structural data from the internal Humber zone. (a) S1 from the Mont Logan nappe. (b) S2 from the Mont Logan nappe. (c) S1 from the Lac Cascapédia window. (d) S2 from the Lac Cascapédia window.

is contemporaneous with D1 in the Mont Logan nappe further north [*Sacks et al.*, 2004]. The high-temperature deformation features of the footwall are cut by brittle to brittle/ductile fabrics that are also present in the Silurian-Devonian rocks of the hanging wall, south of the Shickshock Sud fault [*Sacks et al.*, 2004]. The late dextral strike-slip motion is interpreted as Acadian in age [*Sacks et al.*, 2004].

[20] A steeply dipping penetrative axial-planar crenulation cleavage S2 (Figure 8d) is associated with NE-trending F2 folds in the Mont Logan nappe and the Lac Cascapédia window (Figures 2 and 3). F2 folds are open, upright or

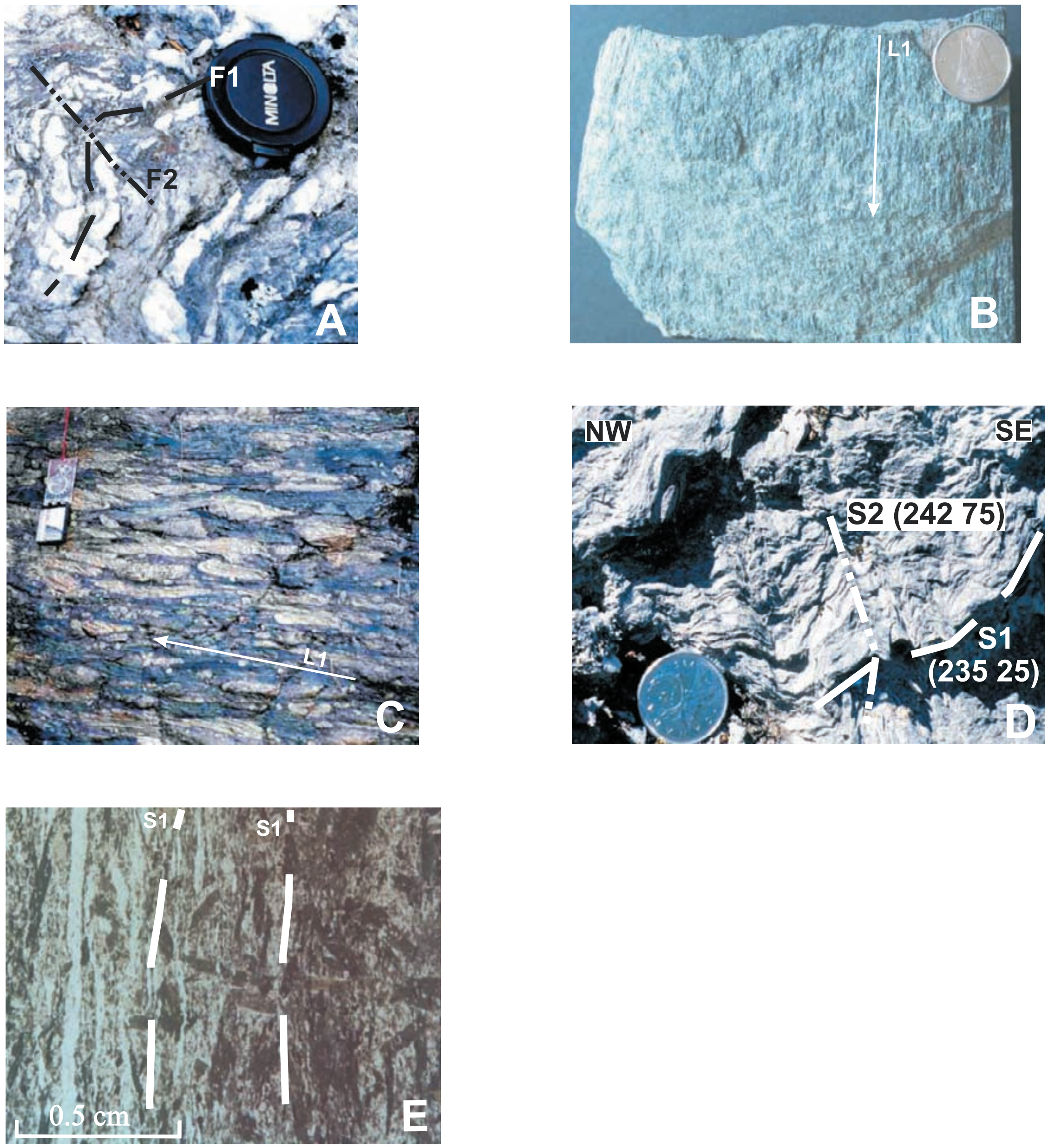

Figure 8. (a) Isoclinal F1 folds in the Mont Logan nappe folded by F2. (b) Elongation lineation in metabasalt marked by chlorite and epidote. (c) Stretching pebbles marking an elongation lineation in the conglomerate of the Shickshock Group. (d) Photograph of the axial-planar cleavage S2 which crenulated the S1 axial-planar cleavage in the schists of the Lac Cascapédia window. (e) Microphotograph of an amphibolite with two generations of hornblendes. The first generation underlines S1.

inclined to the SE or NW, and have axes plunging to the SW or NE (Figure 2) [*Beaudin*, 1980, 1984; *Camiré*, 1995]. S2 is a penetrative crenulation cleavage which is not associated with any apparent metamorphic paragenesis. S2 dips steeply to the SE or NW (Figures 7b and 7d). The mean attitude of S2 is highly variable with a general dip to the SE within the Mont Logan nappe, whereas the mean attitude of S2 is N240°/77 within the Lac Cascapédia window (Figure 7d). The β pole to S1 indicates that F2 folds plunge very gently to the SW in both domains (Figures 7b and 7d), which is also indicated with the intersection lineation L_{1-2} (Figure 9).

[21] As a whole, rocks of the Lac Cascapédia window and of the Mont Logan nappe share a common structural evolution with the same structural features, a folded metamorphic S1 foliation and a subvertical, NE-trending, crenulation cleavage S2, axial-planar to F2. Folding of the Lac Cascapédia fault representing the border between the two domains is attributed to D2 [*Beaudin*, 1984] (Figure 3).

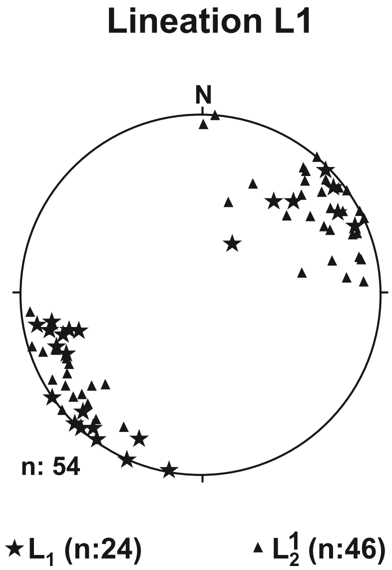

Figure 9. Lineation in the internal Humber zone (L1 and L1–2).

4.4. External Humber Zone

[22] Rocks in the external Humber zone are less deformed and metamorphosed (prehnite-pumpellyite metamorphic grade) than those of the internal Humber zone to the south (greenschist/amphibolite metamorphic grade). The bedding S0 is affected by an axial-planar slaty cleavage S1 and a spaced crenulation cleavage S2 which is best-developed to the south, near the boundary with the internal zone (Figure 3). The first deformation in the external zone is characterized by S to SE-dipping thrust faults, contemporaneous with NE-trending F1 folds with the axial planar cleavage S1 that dips to the SE [*Slivitzky et al.*, 1991]. The attitudes of S0 and S1 are shown on stereoplots (Figures 10a and 10b). The β pole to S0 indicates that F1 folds plunge gently to the ENE (Figure 10a). S1 is NE-trending and dips steeply mainly to the SE with minor dips to the NW (Figure 10b). The intersection lineation L_{0-1} plunges also shallowly NE and SW (Figure 10c). The late S2 cleavage is trending NE and dipping moderately to the NW or shallowly to the SE (Figure 10b).

4.5. Spatial Structural Relationships and Kinematics of Taconian Deformation in the Humber Zone

[23] Folding and thrust faulting appear to be coaxial in internal and external Humber zones, which may indicate that they are the result of a protracted NW–SE shortening event along the Laurentian continental margin. The structure of the internal zone is, however, more complex than in the external zone owing to the superposition of penetrative D2 deformation and to well-developed regional metamorphism (greenschist to amphibolite grade). The older synmetamorphic D1 thrust faults, such as the Lac Cascapédia fault at the base of the Mont Logan nappe, are folded by D2 in the internal Humber zone (Figure 3). The external zone is characterized by NW-directed thrusts and overturned folds with an associated axial-planar cleavage and very low grade metamorphism [*Islam et al.*, 1982]. The late S2 cleavage is only developed southward, close to the Shickshock Nord fault.

[24] The overall structural transport of Taconian nappes in the Humber zone of Gaspé Peninsula corresponds to in-sequence thrusting with younger faults formed in the direction of structural transport toward the north (Figure 4). This piggyback stacking of nappes placed older

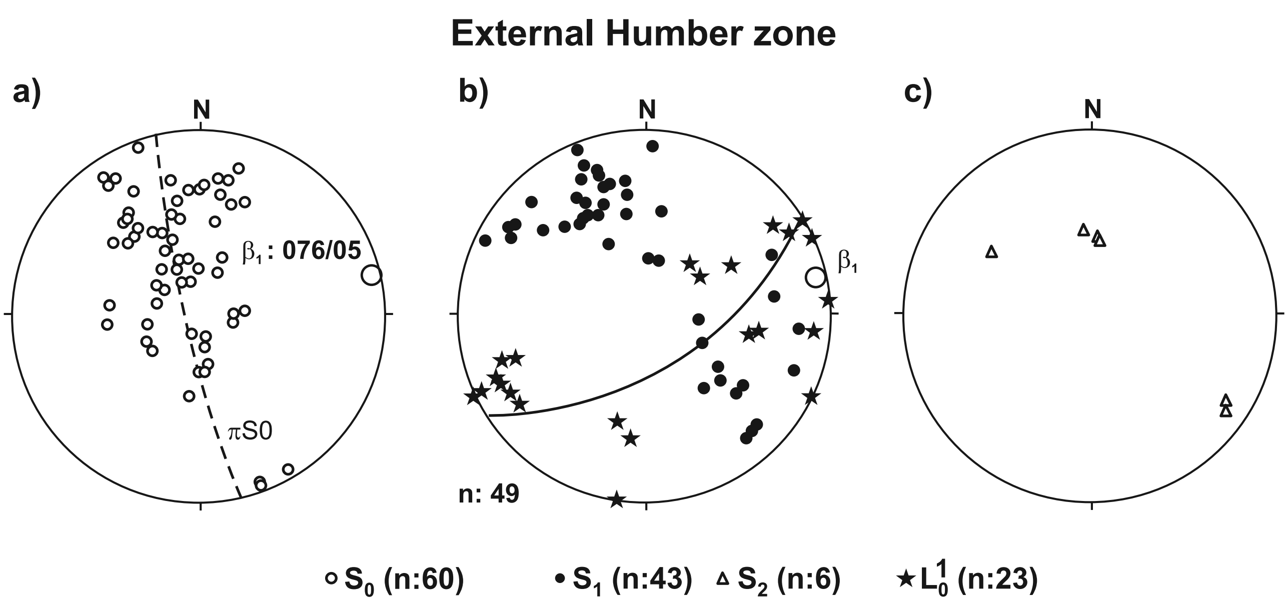

Figure 10. Stereoplots of structural data from the external Humber zone. (a) S0. (b) S1 and L0–1. (c) S2.

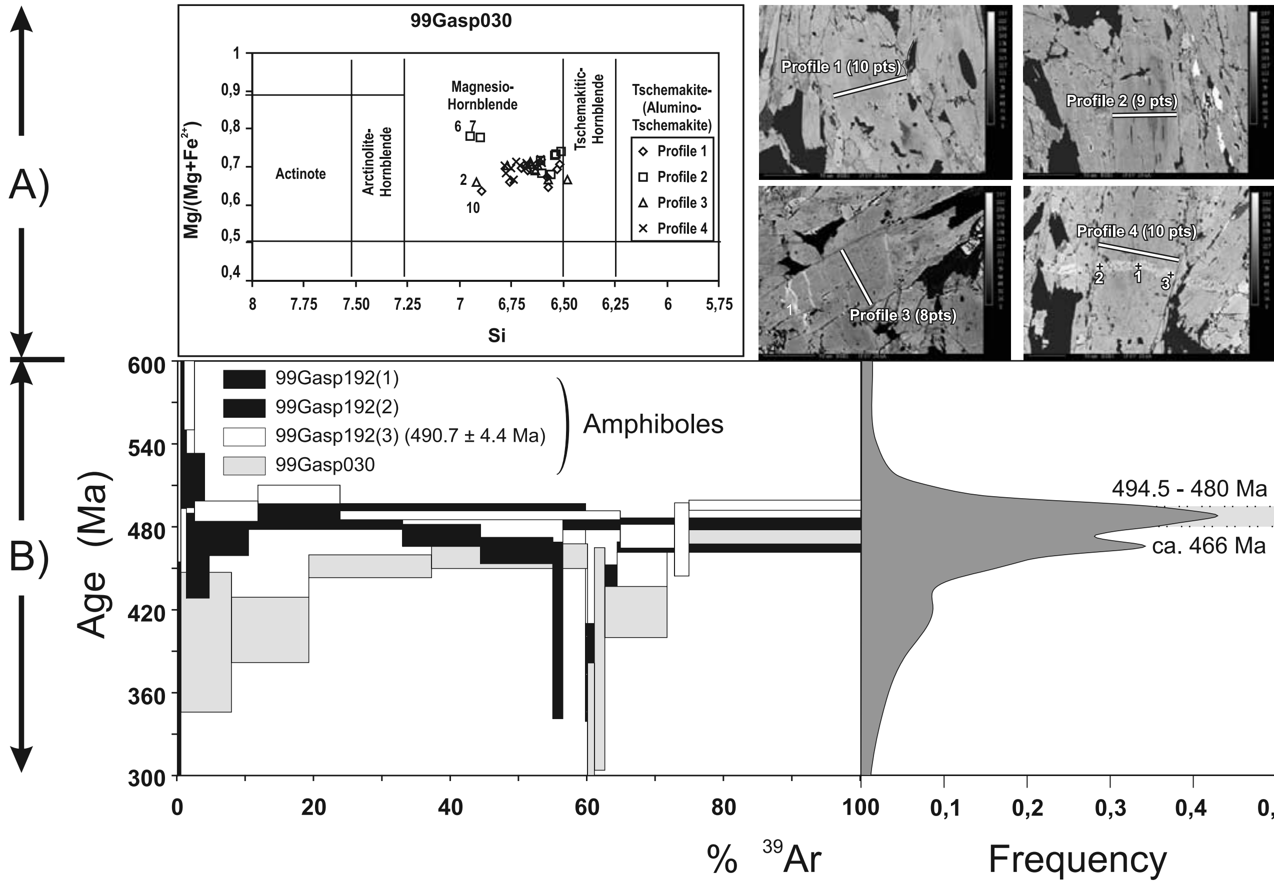

Figure 11. (a) Microprobe chemical analyses of amphibole 99Gasp030. Data are presented as variation in Mg/Mg + Fe^{2+} and Si^{4+} in coefficients of structural formula of amphibole based on 23 oxygen atoms, and plotted on the calcic amphibole classification of *Leake* [1978]. (b) The $^{40}Ar/^{39}Ar$ age spectra and frequency diagram of apparent ages of amphiboles from the amphibolite metamorphic facies of the Shickshock Group (pre-D1 event). The age error bars for each temperature steps are at the 1σ level. The errors in the J-values are not included. Plateau ages (2σ uncertainties) are given when applicable. See Figures 1 and 2 for samples location and text for discussion.

rocks on younger rocks. The older Neoproterozoic-Cambrian rocks of the Shickshock Group within the Mont Logan nappe were transported over the Cambrian-middle Ordovician rocks of the Rivière Saint-Anne nappe, which were transported over middle Ordovician rocks of the Rivière Marsoui nappe. The final thrusting placed these latter middle Ordovician rocks over the younger late Ordovician rocks of the parautochthonous zone (Figures 1 and 4). The NW-directed structural transport of nappes is indicated mainly by NE-trending overturned F1 folds and by NE-trending and SE-dipping F1 axial surface in the external Humber zone (Rivière Sainte-Anne and Rivière Marsoui nappes). On the other hand, this nappe transport direction is perpendicular to the NE-trending stretching lineation L1 in the internal Humber zone (Mont Logan nappe). This type of penetrative lineation usually indicates the line of transport [*Davis and Reynolds*, 1996]. The kinematic model that will be presented below for Taconian deformation of the Humber zone of the Gaspé Peninsula must therefore reconcile the NE-trending orogen-parallel lineation with the overall orogen-orthogonal structural transport of nappes toward NW.

5. The $^{40}Ar/^{39}Ar$ Geochronology

5.1. Analytical Procedure

[25] Single grains of biotite, muscovite and amphibole used for the experiments were handpicked under a binocular microscope from 0.25 to 1.0 mm fractions of crushed rock samples. The samples were wrapped in Al foil to form small packets (11 × 11 mm) that were stacked up to form a pile within which packets of fluence monitors were inserted every 8–10 samples. Two irradiations were performed at the McMaster reactor (Hamilton, Canada). The first irradiation lasted 150 h (total fluence of 9×10^{18} n.cm^{-2}) and concerned most of the samples. The second irradiation lasted 70 h (total fluence of 4.2×10^{18} n.cm^{-2}) and concerned 2 samples. In both cases the irradiation standard

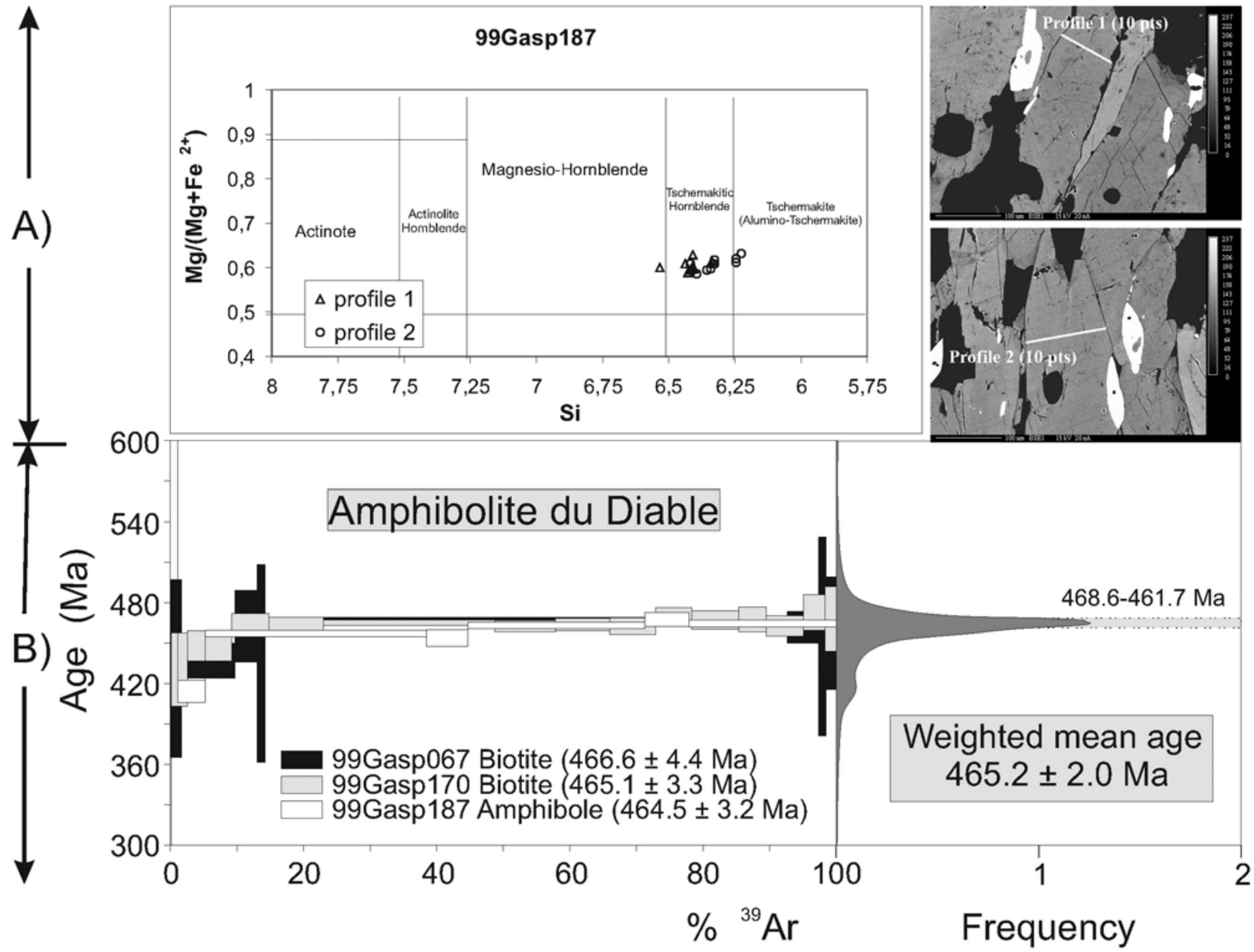

Figure 12. (a) Microprobe chemical analyses of amphibole 99Gasp187. Data are presented as variation in Mg/Mg + Fe^{2+} and Si^{4+} in coefficients of structural formula of amphibole based on 23 oxygen atoms, and plotted on the calcic amphibole classification of *Leake* [1978]. (b) The $^{40}Ar/^{39}Ar$ age spectra and frequency diagram of apparent ages of biotites and amphibole from the Amphibolite du Diable metamorphic sole, early D1. The age error bars for each temperature steps are at the 1σ level. The errors in the J-values are not included. Plateau ages (2σ uncertainties) are given when applicable. See Figure 2 for samples location and text for discussion.

was amphibole Hb3gr (1071.7 ± 5.4 Ma [*Turner et al.*, 1971; *Roddick*, 1983]). The sample arrangement within the irradiation allows us to monitor the flux gradient with a precision as low as ±0.2%.

[26] The step-heating experiment on single grains was described by *Ruffet et al.* [1991, 1995]. Blanks were performed routinely each first or third step, and subtracted from subsequent sample gas fractions. Typical blank values were in the range $2.1 \times 10^{-13} < M/e\ 40 < 5.82 \times 10^{-13}$, $3.9 \times 10^{-15} < M/e\ 39 < 4.2 \times 10^{-14}$, $6.6 \times 10^{-15} < M/e\ 38 < 2.34 \times 10^{-14}$, $1.04 \times 10^{-13} < M/e\ 37 < 1.4 \times 10^{-13}$, $1.74 \times 10^{-14} < M/e\ 36 < 2.97 \times 10^{-14}$ cm^3 STP.

[27] It is commonly considered that a plateau age is obtained when apparent ages of at least three consecutive steps, comprising a minimum of 70% of the ^{39}Ar released, agree within 2σ error bars with the integrated age of the plateau segment. All ages are displayed at the 2σ level.

5.2. Sampling

[28] The aim of our detailed $^{40}Ar/^{39}Ar$ geochronological study was to date the different metamorphic facies in the Taconian hinterland of the Gaspé Peninsula and, combined with the structural analysis of tectonic fabrics, the two phases of penetrative deformation (D1 and D2).

[29] We have sampled (Figure 2) the Amphibolite du Diable metamorphic sole throughout the three ophiolitic klippes (Mont Albert, Mont du Sud and Mont Paul), and the Mont Logan nappe, from the amphibolite facies at contact with the Shickshock Sud fault, to the south, to the greenschist facies further north. We have also specifically sampled amphibolites of the La Rédemption Complex.

[30] The following sections present laser step-heating $^{40}Ar/^{39}Ar$ results on single grains of muscovite, amphibole and biotite (Figures 11–17). Results will be presented

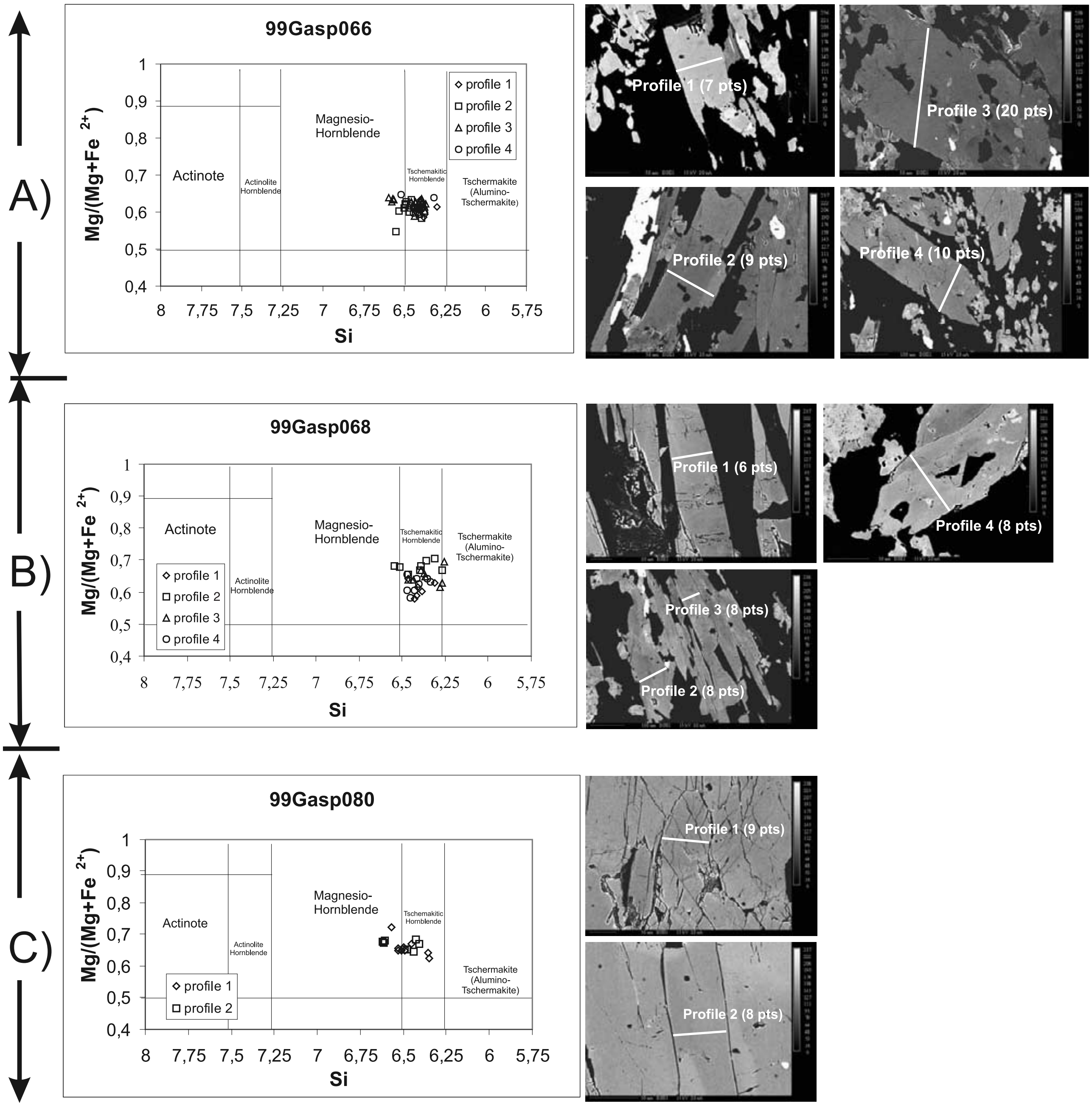

Figure 13. Microprobe chemical analyses of amphiboles (a) 99Gasp066, (b) 99Gasp068, and (c) Gasp080. Data are presented as variation in Mg/Mg + Fe^{2+} and Si^{4+} in coefficients of structural formula of amphibole based on 23 oxygen atoms, and plotted on the calcic amphibole classification of *Leake* [1978].

according to the tectonic setting of metamorphic facies and the relative chronology to the main deformation phase D1. Complete $^{40}Ar/^{39}Ar$ step-heating data and location coordinates of sampling sites are available upon request.

5.3. Pre-D1 Event in the Amphibolite Metamorphic Facies of the Shickshock Group

[31] Amphibolite samples 99Gasp192 and 99Gasp030 were collected from metabasalts of the Shickshock Group in the close vicinity of (or within) the Shickshock Sud fault. Amphibolite 99Gasp192 was collected in metabasalt of the La Rédemption Complex (Figure 1), whereas 99Gasp030 comes from metabasalt of the Mont Logan nappe (Figure 2).

[32] Amphiboles from these samples are not always aligned within S1 foliation. Sample 99Gasp192 is an amphibolite with small hornblende crystals. Texture of amphibolite 99Gasp030 is more or less cataclastic. Amphibole crystals from this sample have prismatic or acicular

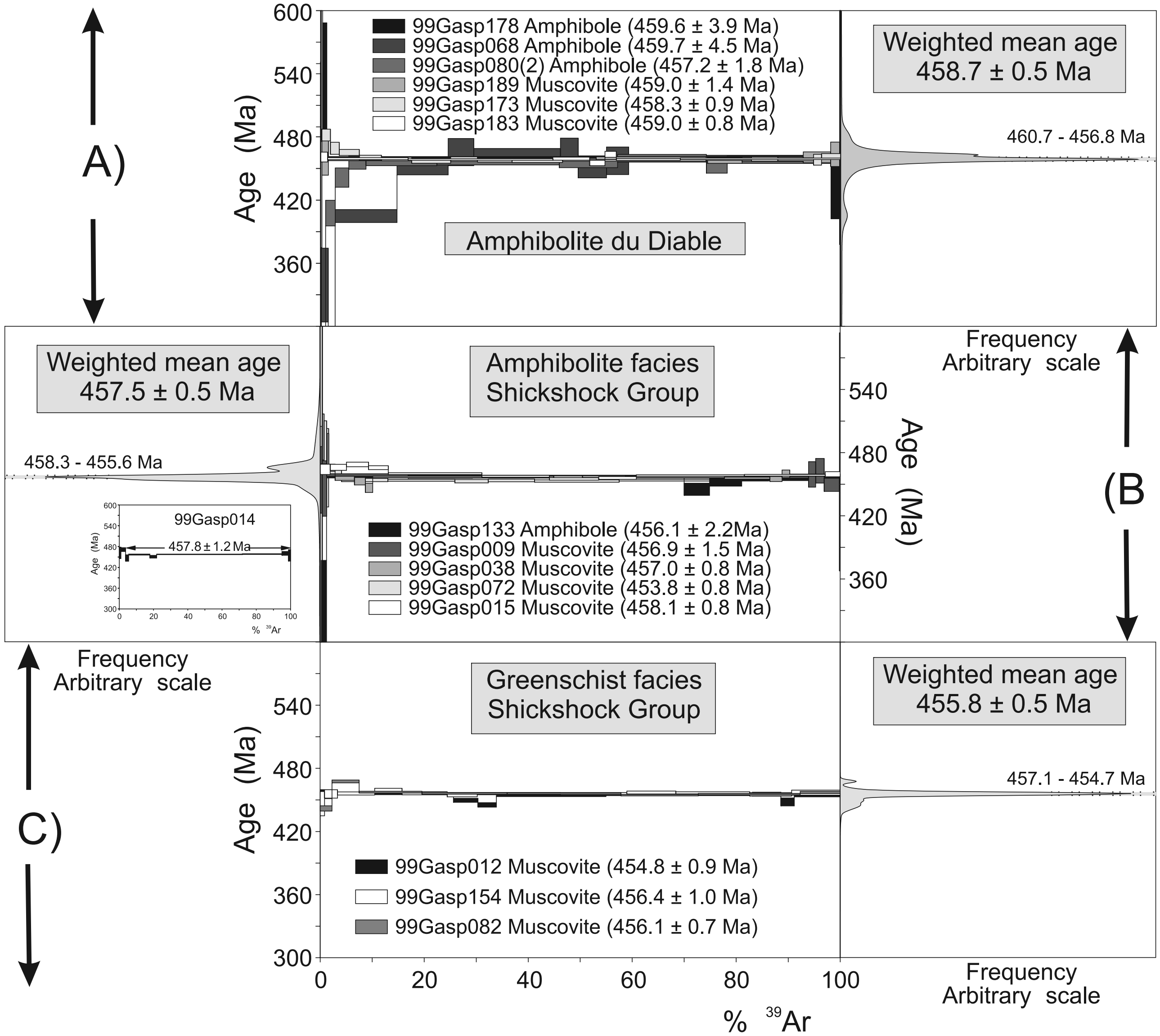

Figure 14. The $^{40}Ar/^{39}Ar$ age spectra and frequency diagram of apparent ages of late D1 (a) amphiboles and muscovites from Amphibolite du Diable metamorphic sole, (b) amphibolite metamorphic facies of Shickshock Group, and (c) greenschist metamorphic facies of Shickshock Group. The age error bars for each temperature steps are at the 1σ level. The errors in the J-values are not included. Plateau ages (2σ uncertainties) are given when applicable. See Figure 2 for samples location and text for discussion.

shapes and some of them are zoned. The SEM images (backscattered electrons) show darker domains in the center of some of the amphibole grains. As variations in color (light versus dark domains) reflect the variation in average atomic number in the mineral, the most likely interpretation of this difference is that the chemical compositions of the two domains are slightly different. Unlike other amphiboles from this study, which are more generally tchermakitic hornblendes, electron microprobe analyses performed on amphiboles from sample 99Gasp030 show that they are magnesio-hornblendes and dark domains have higher Mg and Si contents and higher Ca/K ratios than the light ones (see profile 2, Figure 11a).

[33] Among the three analyses performed on amphibole 99Gasp192, only the third one yielded a plateau age, at 490.7 ± 4.4 Ma (Figure 11b). All other analyses displayed disturbed age spectra with either a staircase shape (99Gasp030) or a saddle shape (99Gasp192 (1) and (2)) (Figure 11b). The frequency diagram of apparent ages of the four experiments defines two frequency peaks, the large one at ~488 Ma which mainly corresponds to the high-temperature apparent ages of experiments and a small secondary one, at ~466 Ma, which characterizes saddle minima of age spectra. The main apparent age peak at ~488 Ma could correspond to degassing of the remnant cores observed on some amphibole grains from sample 99Gasp030 whereas disturbances

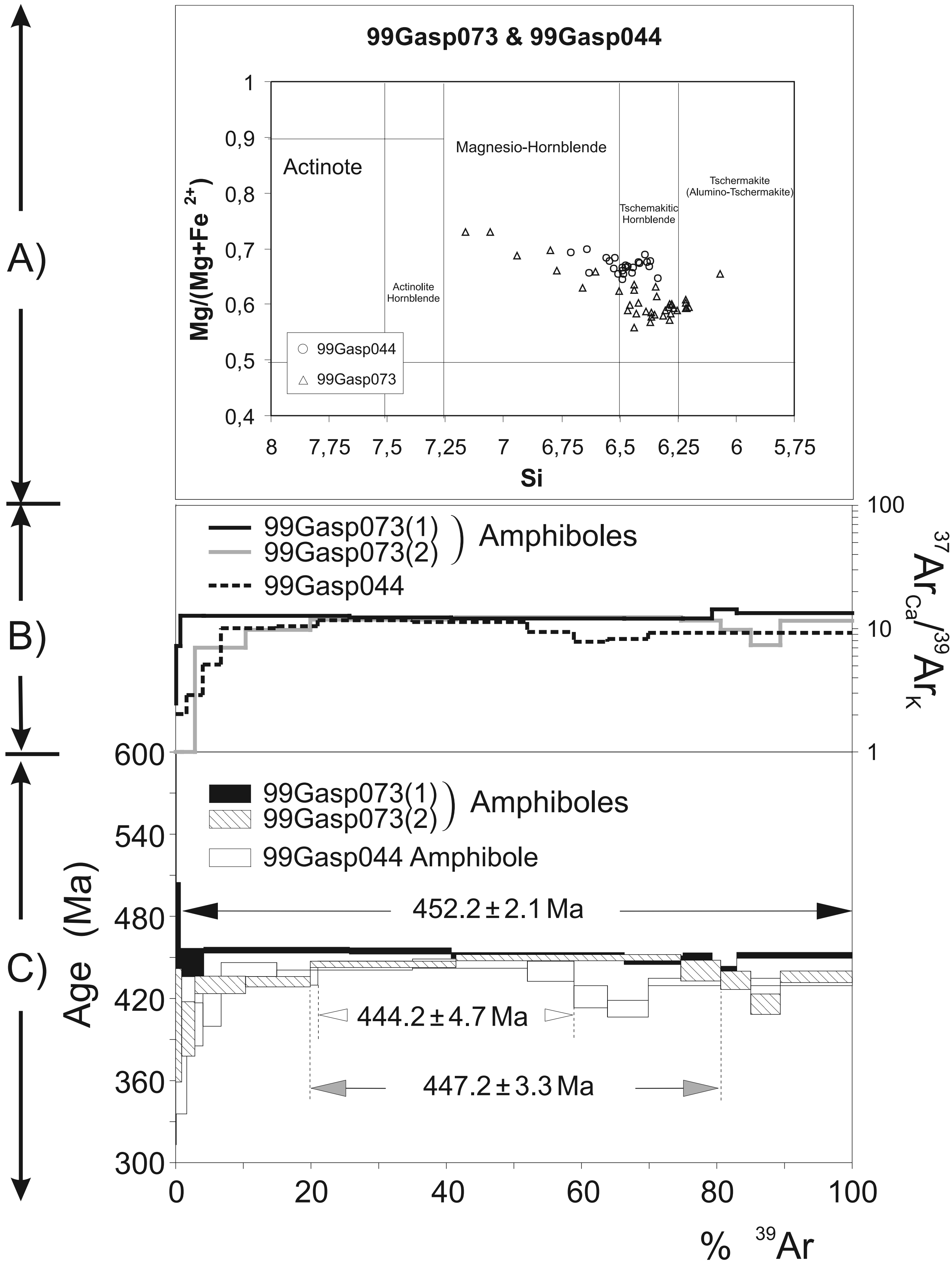
A)
B)
C)
99Gasp073 & 99Gasp044
Actinote
Magnesio-Hornblende
Actinolite Hornblende
Tschemakitic Hornblende
Tschermakite (Alumino-Tschermakite)
99Gasp044
99Gasp073
Mg/(Mg+Fe 2+)
Si
99Gasp073(1)
99Gasp073(2)
Amphiboles
99Gasp044
37ArCa/39ArK
99Gasp044 Amphibole
452.2 ± 2.1 Ma
444.2 ± 4.7 Ma
447.2 ± 3.3 Ma
Age (Ma)
% 39Ar

Figure 15

(younger ages) could be related to the evidenced core to rim gradient [e.g., *Ruffet et al.*, 1990; *Castonguay et al.*, 2001].

5.4. First Deformation Phase D1

[34] The main tectonic fabric throughout the study area is the oldest foliation recognized in every tectonic domain which is assigned to D1. All the analyzed minerals underline foliation S1.

5.4.1. Early D1 in the Amphibolite du Diable Metamorphic Sole

[35] Three samples were collected in the amphibolitic soles of the Mont Albert and Mont du Sud klippes. Sample 99Gasp187 is an amphibolite from slice 2 of the Amphibolite du Diable as defined by *Gagnon and Jamieson* [1986] with subautomorph unzoned amphibole crystals. Sample 99Gasp170 is a biotite-muscovite schist from the same slice, whereas sample 99Gasp067 is a biotite-muscovite schist from the amphibolitic sole of Mont du Sud (Figure 2).

[36] Electron microprobe analyses performed on amphibole 99Gasp187 show that it is a tchermakitic hornblende with unzoned crystals (Figure 12a).

[37] One amphibole (99Gasp187) and two biotites (99Gasp170 and 99Gasp067) were analyzed. The three experiments displayed three concordant plateau ages (Figure 12b) with a weighted mean age at 465.2 ± 2.0 Ma. The slight staircase shape of the amphibole age spectrum could suggest a small disturbance of its isotopic system during a subsequent event [e.g., *Castonguay et al.*, 2001]. The frequency diagram of apparent ages defines a sharp peak at 464.7 Ma (Figure 12b), concordant with the weighted mean of plateau ages. It is worth noting that these analyzed minerals (probably amphibole and assuredly biotite) are inherited phases "preserved" in the main foliation S1. These minerals probably recrystallized during the first increment of D1 (early D1, Figure 4).

5.4.2. Late D1

[38] Analyzed minerals (probably amphibole and assuredly muscovite) are not inherited minerals. As they underline S1 foliation, their crystallization and growth are closely related to D1.

5.4.2.1. Late D1 in the Amphibolite du Diable Metamorphic Sole

[39] Six samples were collected in slices 2 and 3 of the Amphibolite du Diable at the Mont Albert klippe and in the amphibolitic sole of Mont du Sud. The two amphibolites 99Gasp080 and 99Gasp178 and the mica schist sample 99Gasp189 (Figure 2) were collected in slice 2 of Amphibolite du Diable. Amphibolite 99Gasp068 was collected at the Mont du Sud klippe (Figure 2). The two other samples (99Gasp173 and 99Gasp183, Figure 2) are mica schists which were collected in slice 3 of the Amphibolite du Diable.

[40] Electron microprobe analyses performed on amphiboles from samples 99Gasp068 and 080 show slightly different compositions, respectively magnesio to tchermakitic hornblende versus tchermakitic hornblende, but in both cases reveal unzoned crystals (Figures 13b and 13c). In the same way, electron microprobe analyses performed on white micas from sample 99Gasp183 [*Pincivy et al.*, 2003] show that they are slightly phengitic (Si^{4+} at ~6.3 pfu) and that there is no core to rim variation.

[41] The six experiments yielded concordant plateau ages (Figure 14a) with a weighted mean age at 458.7 ± 0.5 Ma. The frequency diagram of apparent ages defines a very sharp peak at 458.8 Ma in perfect agreement with the weighted mean of plateau ages.

[42] The highly concordant ages obtained on muscovites and amphiboles support hypothesis that cooling was very rapid and thus the age at ~459 Ma is nearly the age of the late increments of D1 (late D1, Figure 4) within the metamorphic soles of ophiolitic klippes. The corollary of this is that the formation of the three ophiolitic klippes is synchronous and these klippes were part of a unique larger ophiolitic nappe.

5.4.2.2. Late D1 in the Amphibolite Metamorphic Facies of the Shickshock Group

[43] Five of the six samples were collected in the amphibolite metamorphic facies of the Shichshock Group within the Mont Logan nappe. Sample 99Gasp133 (Figure 2) is an amphibolite (metabasalt) with subautomorph hornblende crystals. The remaining four samples (99Gasp009, 99Gasp038, 99Gasp072 and 00Gasp015) were collected from mica schists (Figure 2). The sixth sample 99Gasp014 is a mica schist with garnet from the La Rédemption Complex (Figure 1).

[44] Electron microprobe analyses performed on amphiboles from sample 99Gasp133 indicate that they are unzoned magnesio- to tchermakitic hornblendes [*Pincivy et al.*, 2003].

[45] The six ^{39}Ar-^{40}Ar experiments (Figure 14b) display five concordant plateau ages and a slightly younger one (Sample 99Gasp072). Apparent age frequency diagram displays a very sharp peak at 457.0 Ma in good agreement with the weighted mean of plateau ages at 457.5 ± 0.5 Ma (Sample 99Gasp072 excluded, see below). As for the samples in the Amphibolite du Diable yielding an age at ~459 Ma (see section 5.4.2.1), highly concordant ages obtained on muscovites and amphibole suggest a rapid cooling. Therefore it is reasonable to view that D1 in the

Figure 15. (a) Microprobe chemical analyses of amphiboles 99Gasp073 and 99Gasp044. Data are presented as variation in Mg/Mg + Fe^{2+} and Si^{4+} in coefficients of structural formula of amphibole based on 23 oxygen atoms, and plotted on the calcic amphibole classification of *Leake* [1978]. (b) The $^{37}Ar_{Ca}/^{39}Ar_K$ age spectra and (c) $^{40}Ar/^{39}Ar$ spectra of amphiboles 99Gasp073 and 99Gasp044. The age error bars for each temperature steps are at the 1σ level. The errors in the J-values are not included. Plateau ages (2σ uncertainties) are given when applicable. See Figure 2 for samples location and text for discussion.

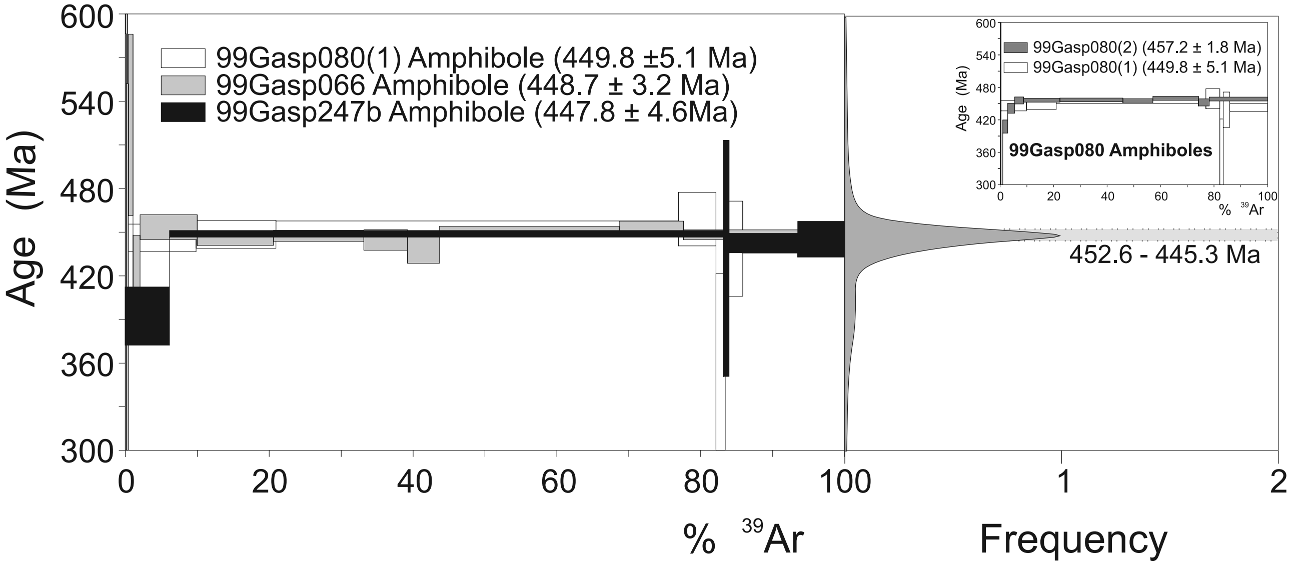

Figure 16. The $^{40}Ar/^{39}Ar$ age spectra and frequency diagram of apparent ages of D2 amphiboles from Amphibolite du Diable metamorphic sole and Mont Logan nappe. The age error bars for each temperature steps are at the 1σ level. The errors in the J-values are not included. Plateau ages (2σ uncertainties) are given when applicable. See Figure 2 for samples location and text for discussion.

amphibolite metamorphic facies of the Mont Logan nappe ended at ~457.5 Ma. It is worth noting that the youngest plateau age (453.8 ± 0.8 Ma; muscovite 99Gasp072) is yielded by a slightly saddle shaped age spectrum. Age spectra with a saddle shape were observed on single grains of muscovite and explained by the mixing between two domains with distinct ages within grains, an inherited domain and a recrystallized or neocrystallized domain [*Alexandrov et al.*, 2002], linked or not to deformation [*Cheilletz et al.*, 1999; *Tremblay et al.*, 2000; *Castonguay et al.*, 2001; *Alexandrov et al.*, 2002]. Such feature could be related to a post-D1 disturbance (see section 5.4.2.3). On the other hand, muscovite 99Gasp015 age spectrum (Figure 14b) displays a similar shape without significant apparent impact on the age.

[46] These results suggest that the end of the D1 (late D1, Figure 4) within the amphibole metamorphic facies of the Mont Logan nappe occurred slightly after the "same" event within the amphibolitic sole (457.5 ± 0.5 Ma versus 458.7 ± 0.5 Ma).

5.4.2.3. Late D1 in the Greenschist Metamorphic Facies of the Shickshock Group

[47] Three mica schist samples were collected in the greenschist metamorphic facies of the Shickshock Group in the Mont Logan nappe, samples 99Gasp154, 99Gasp082 and 99Gasp012 (Figure 2).

[48] The similar compositions of cores and rims in all samples as revealed by electron microprobe analyses indicate that there is no chemical zoning within individual crystals [*Pincivy et al.*, 2003]. Results show a slight deviation toward phengite pole from muscovite end-member for sample 99Gasp082 whereas white micas from sample 99Gasp154 clearly have a more phengitic composition. Analyses performed on white micas from sample 99Gasp012 reveal a slight deviation from the muscovite-phengite line toward the ferrimuscovite pole.

[49] All experiments yielded very concordant plateau ages with a weighted mean age at 455.8 ± 0.5 Ma (Figure 14c). The frequency diagram of apparent ages defines a very sharp peak at 456.0 Ma, in perfect agreement with the weighted mean of plateau ages, but slightly younger than the age at 457.5 ± 0.5 Ma displayed by samples from the amphibolite metamorphic facies of the Shickshock Group. More obviously than for samples from the amphibole metamorphic facies, the age at ~456 Ma on

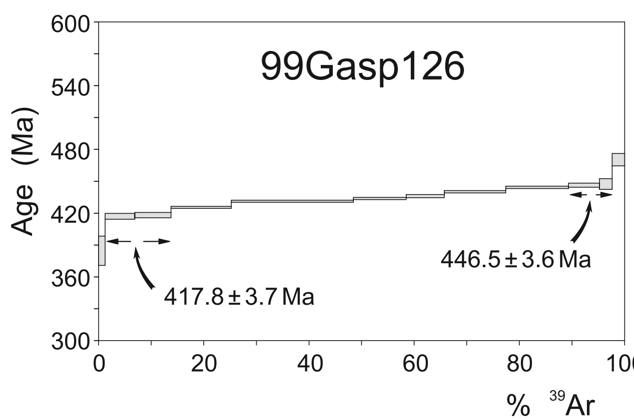

Figure 17. The $^{40}Ar/^{39}Ar$ age spectrum of muscovite 99Gasp126. The age error bars for each temperature steps are at the 2σ level. The errors in the J-values are not included. See Figure 2 for sample location and text for discussion.

muscovites from greenschist metamorphic facies is nearly a crystallization age, close to the end of the late D1 north of the amphibolite facies isograd of the Mont Logan nappe.

5.5. Younger Deformation Events

5.5.1. D2 in the Hinterland: Amphibolite du Diable Metamorphic Sole and Mont Logan Nappe

[50] Younger ages or concomitant disturbed age spectra were obtained on samples which frequently present specificities such as the presence of two amphibole generations or the existence of a crenulation cleavage S2. These particularities are mainly observed on amphibole minerals but muscovites are not spared.

[51] Three amphiboles from amphibolites collected in the metamorphic sole, (99Gasp080 and 99Gasp247b at Mont Albert, 99Gasp066 at Mont du Sud) yield younger concordant plateau ages (Figure 16) with an apparent age frequency peak at 449.0 Ma (Figure 16) concordant with the weighted mean of plateau ages at 448.7 ± 2.3 Ma. Experiment 99Gasp080(1) is a duplicate analysis performed on an amphibole from sample 99Gasp080 (see amphibole 99Gasp080(2) from section 5.4.2.1. with a plateau age at 457.2 ± 1.8 Ma).

[52] Two generations of amphiboles can be observed in sample 99Gasp066, the first one underlines foliation S1 whereas the second one, with bigger subautomorph crystals, crosscut this foliation (Figure 8e). On the other hand, only one amphibole generation can be observed in sample 99Gasp080. Electron microprobe analyses performed on amphiboles from samples 99Gasp066 show that both amphibole generations are magnesio to tchermakitic hornblendes and that crystals are unzoned (Figure 13a). Note that sample 99Gasp080 yields similar electron microprobe results with also a lack of amphibole zoning (Figure 13c).

[53] In sample 99Gasp066, the sizable size and subautomorph nature of the amphiboles of second generation against ones of the first generation (which underline foliation S1) suggest that it is highly probable that the analyzed amphibole, which was handpicked under binocular microscope on shape criteria, was an amphibole grain of second generation. In sample 99Gasp080, with apparently only one amphibole generation, the two ^{39}Ar-^{40}Ar analyses performed display two distinct plateau ages (Figures 14a and 16). As the oldest obtained age was clearly linked with D1 (see above), we assume that the younger one characterizes a subsequent event that could be D2.

[54] Two amphibolites, 99Gasp073 from amphibolitic sole at Mont Paul and 99Gasp044 from amphibolite metamorphic facies of the Shickshock Group in the Mont Logan nappe (Figure 2) displayed disturbed amphibole ^{39}Ar-^{40}Ar age spectra with characteristic shapes (Figure 15c). In both samples foliation S1 is crenulated and folded by S2. Electron microprobe analyses performed on amphiboles from sample 99Gasp073 and, with less extent sample 99Gasp044, show in some grains compositional gradients from core (magnesio-hornblende) to rim (tchermakitic hornblende) (Figure 15a). These gradients can be correlated with SEM images (backscattered electrons) showing darker domains in the center of some of the analyzed amphibole grains.

[55] The two experiments labeled (1) and (2) performed on amphibole 99Gasp073 yielded two distinct age spectra shapes, a saddle shape (99Gasp073(1)) with age minima at ~450 Ma (~34% of $^{39}Ar_K$) and a slight hump shape (99Gasp073(2)) with a pseudo plateau age at 447.2 ± 3.3 Ma (Figure 15c). The age of the saddle minimum is concordant with the age of the hump maximum. As previously explained (see section 5.4.2.2.), saddle-shaped age spectra observed on muscovites can be explained by the mixing between two domains with distinct ages, an inherited domain and, a recrystallized or neocrystallized domain. We propose that similar shape could be explained in the same way for amphiboles, that is to say an isotopic system initially closed at 459 Ma followed by a disturbing event at ~448.5 Ma. The $^{37}Ar_{Ca}/^{39}Ar_K$ spectra of the two experiments performed on sample 99Gasp073 (Figure 15b) present also two distinct shapes, a flat pattern for experiment 99Gasp073(1), characteristic of the degassing of an unaltered amphibole and a hump shape for experiment 99Gasp073(2) that could suggest a slight "alteration" of the analyzed grain detectable in the low- and high-temperature degassing domains. The concordance of the two $^{37}Ar_{Ca}/^{39}Ar_K$ spectra in the intermediate temperature domain confirms the validity of ages in this temperature domain, at ~448.5 Ma. $^{37}Ar_{Ca}/^{39}Ar_K$ spectrum of amphibole 99Gasp044 shows a more pronounced shape than for amphibole 99Gasp073(2) that could suggest a more consequent alteration and explain the slightly younger age at 444.2 ± 4.7 Ma.

[56] In addition to the five samples discussed in the sixth group, three other white micas could also have "registered" the D2. In samples 99Gasp082 and 00Gasp015, foliation S1 is folded and crenulated by S2. Analyses performed on white micas from these two samples yielded slightly saddle shaped age spectra (Figure 14c). As briefly discussed above, this shape could attest that the isotopic system of these two white micas was disturbed during D2, subsequently to their crystallization which occurred during D1. On the other hand, muscovite 99Gasp072 which underlines S1 yielded also a slightly saddle shaped age spectrum (Figure 14b) even if the sample does not show traces of D2 related deformation (crenulation of S1).

5.5.2. Salinic Disturbance?

[57] Sample 99Gasp126 is a mica schist from the Shickshock Group with sericite sampled at the contact with the Shickshock Sud fault (Figure 2). Sericite underlines foliation S1. This foliation is crenulated and folded during D2. There is no evidence for a paragenesis associated to D2.

[58] The analyzed white mica displays a staircase shaped age spectrum (Figure 17), with ages ranging from ~418 Ma in the low-temperature steps to ~447 Ma in the high temperature steps (fusion step excepted). Such shape could characterize, as proposed by *West and Lux* [1993], the disturbance of the K-Ar isotopic system of white micas related to deformation. As white micas grew during D1, we propose that the analyzed grain was first completely resetted during D2 at ~447 Ma and then disturbed during a subsequent event, at ~418 Ma (Salinic disturbance, Figure 4).

5.6. Discussion on ^{39}Ar-^{40}Ar Results

[59] Quite obviously amphiboles displayed more information than white micas. One of the reasons is probably the early crystallization of amphiboles in the tectono-metamorphic history, in comparison with white micas but there are probably other reasons.

[60] Electron microprobe analyses performed on amphiboles from various samples show that most of them are "tchermakitic" hornblendes. Nevertheless, three samples show different results: (1) all analyzed amphiboles from sample 99Gasp030 are in the field of magnesio-hornblendes with rather scattered results; these amphiboles have higher CaO/K_2O ratios than tchermakitic hornblendes from other samples; (2) some amphibole grains from samples 99Gasp073 and 99Gasp044 show rim to core compositional gradients; one of the effects is an increase of the CaO/K_2O ratio from rim to core.

[61] $^{37}Ar_{Ca}/^{39}Ar_K$ ratios measured during ^{39}Ar-^{40}Ar analysis of an amphibole grain from sample 99Gasp030 are compatible with electron microprobe results. CaO/K_2O ratios as high as $\sim$100 (using conversion formula: $CaO/K_2O = 2.179 \times (^{37}Ar_{Ca}/^{39}Ar_K)$ [*Castonguay et al.*, 2001]) are measured/calculated during ^{39}Ar-^{40}Ar step-heating analyses (against ratio of $\sim$110 for electron microprobe analyses). On the other hand, none of the $^{37}Ar_{Ca}/^{39}Ar_K$ ratios (Figure 15b) measured from samples 99Gasp073 and 99Gasp044 during ^{39}Ar-^{40}Ar analyses (using conversion formula: $CaO/K_2O = 2.179 \times (^{37}Ar_{Ca}/^{39}Ar_K)$ [*Castonguay et al.*, 2001]) is compatible with the high CaO/K_2O ratios shown with electron microprobe analyses in cores of some amphibole grains from these same samples. For this reason, it is highly probable that amphibole grains selected for ^{39}Ar-^{40}Ar laser probe analyses from samples 99Gasp073 and 99Gasp044 were tchermakitic hornblendes.

[62] It seems that all amphibole grains which were analyzed with the ^{39}Ar-^{40}Ar method (sample 99Gasp030 excepted) were probably tchermakitic hornblendes (or magnesio- to tchermakitic hornblendes). Nevertheless, the K-Ar isotopic system of amphiboles registered at least two metamorphic events, D1 and D2. So, at first sight, there is apparently no parallelism between the chemical composition of the analyzed grains and the behavior of their isotopic system. For instance, amphiboles from samples 99Gasp068 and 99Gasp066, with nearly identical chemical compositions, display plateau ages as different as 459.7 ± 4.5 Ma and 448.7 ± 3.2 Ma, respectively. Two amphibole generations can be observed within sample 99Gasp066, the first generation underlines foliation S1 and could allow dating D1 whereas the second generation crosscuts, and then postdates this foliation and allowed to date D2. Nevertheless electron microprobe analyses performed on amphiboles from sample 99Gasp066 do not allow differentiating these two amphibole populations. In the same way, the two ^{39}Ar-^{40}Ar experiments performed on two amphibole grains from sample 99Gasp080 yield two distinct plateau ages at 457.2 ± 1.8 Ma and 449.8 ± 5.1 Ma. Yet, electron microprobe analyses show a homogeneous chemical composition of amphibole grains in this sample. Therefore, such features could indicate that events D1 and D2 occurred under the same P-T conditions. This could also explain the apparent lack of paragenesis associated to D2 [*Pincivy*, 2003; *Pincivy et al.*, 2003].

6. A Geodynamic Interpretation

[63] The age of Taconian deformation in the Humber zone of the Quebec Appalachians was traditionally constrained by the age of fossiliferous olistostromal deposits (early to middle Late Ordovician; graptolites from *Nemagraptus gracilis* to *Orthograptus ruedemanni* Zones or 460.5 Ma to $\sim$453 Ma [*Webby et al.*, 2004]) genetically related to the emplacement of external nappes [*St-Julien and Hubert*, 1975]. It corresponds to the development of the Cap-Chat Mélange in the Gaspé Peninsula along and inboard of Logan's Line (Figure 1 [*Cousineau*, 1998]). Unconformity in which lower Silurian rocks rest unconformably on deformed Cambrian-Ordovician rocks indicates that the Taconian orogeny was finished before early Silurian (Figure 4). The piggyback sequence of nappes stacking in the external Humber zone (Figure 4) supports the traditional thrust tectonics style owing to a head-on orthogonal collision for the Canadian Appalachians [*St-Julien and Hubert*, 1975; *Williams*, 1979; *Waldron et al.*, 1998]. Rocks of the external Humber zone were affected by very low grade metamorphism [*Islam et al.*, 1982] during the Taconian orogeny whereas higher grade metamorphic conditions are recorded in the Taconian hinterland.

[64] Oceanic ferrogabbros of the Amphibolite du Diable at the contact with the Mont Albert Complex (slice 1) have recorded P-T conditions of 750–800°C and 8–9 Kbar [*O'Beirne-Ryan et al.*, 1990]. These conditions decrease to 600–700°C and 6–7 Kbar [*O'Beirne-Ryan et al.*, 1990] in the underlying slice composed of mixed ancient oceanic metaferrogabbros and quartzofeldspatic metasedimentary rocks [*Gagnon and Jamieson*, 1986; *O'Beirne-Ryan et al.*, 1990]. Evidence of retrogressive metamorphism is observed throughout the metamorphic sole [*Gagnon and Jamieson*, 1986; *O'Beirne-Ryan et al.*, 1990]. The Mont Logan nappe structurally below the Amphibolite du Diable and the overlying Mont Albert Complex presents a medium-pressure metamorphic sequence divided into four metamorphic zones, from north to south: actinolite, hornblende, actinolite-out and oligoclase zones [*Camiré*, 1995]. This latter zone, close to the Shickshock Sud fault, recorded P-T conditions at the peak of metamorphism of $\sim$6–7 Kbar and 600–700°C [*Camiré*, 1995]. These zones suggest the existence of a prograde regional metamorphism with the development of an inverted metamorphic sequence related to the thrust fault located at the top of the inverted sequence [*Camiré*, 1995].

[65] Our new geochronological data in the Taconian hinterland of the Quebec reentrant help to define precisely the timing of oceanic and continental geodynamic processes related to emplacement of the ophiolitic nappe onto the Laurentian margin during the closure of the Humber seaway [*Waldron and van Staal*, 2001; *van Staal*, 2005], whereas new structural data help to better define the geodynamic setting and kinematics of this collision which involved

formation of an orogen-parallel lineation within the hinterland.

6.1. Early D1 Deformations: Early Taconian–Intraoceanic Thrusting and Thickening of the Ophiolite Nappe During Translation Toward the Continental Margin

[66] D1 deformation features recorded in rocks of the Taconian hinterland represent the first continental deformation of the Paleozoic Laurentian margin. However, the closure of the adjacent Iapetus oceanic domain and the obduction process started earlier and involved deformation of oceanic rocks due to the intraoceanic thrusting of peridotites on the upper oceanic crust and translation of this ophiolite toward the continental margin (early D1, Figures 4 and 18a). Early D1 deformation occurring in rocks of the oceanic domain is the expression of what we consider as the early Taconian stage (Figure 18a).

[67] Tectonic slice 1 of the Amphibolite du Diable (oceanic ferrogabbros) was formed and metamorphosed at the granulite facies during intraoceanic thrusting of the peridotic nappe [*O'Beirne-Ryan et al.*, 1990]. The high temperature and high pressure metamorphism in the Amphibolite du Diable is indicated by garnet and pyroxene relics. The translation of the ophiolitic nappe toward the continental margin is recorded by the increase of sedimentary components incorporated into successive slices 2 and 3 of the metamorphic sole [*Gagnon and Jamieson*, 1986]. The presence of tholeiitic basalts in slices 3 and 4 also indicates the approach of the peridotite and its metamorphic sole toward the continental margin [*Gagnon and Jamieson*, 1986]. The 465 Ma inherited biotite preserved in the main foliation S1 in the Amphibolite du Diable (samples 99Gasp 067 and 99Gasp170) probably crystallized during early D1. High temperature deformation features in the upper part of the Amphibolite du Diable and the basal part of the peridotites of the Mont Albert Complex [*Sacks et al.*, 2004], along the Mont Albert fault (Figure 3), implies that the ophiolite was hot and young at the time of intraoceanic thrusting, and probably close to where it was generated. We believe that the Mont Albert Complex was generated by peri-collisional spreading in the Quebec reentrant region of the Humber seaway in a suprasubduction zone setting as suggested for the Bay of Island Complex in Newfoundland [*Cawood and Suhr*, 1992] and the Thetford Mines Ophiolite Complex in southern Quebec [*Schroetter et al.*, 2003]. The emplacement of Mont Albert Complex onto the continental margin resulted in the late D1 deformation (see below). We propose that the time lag 465–459 Ma expresses part of the translation of the ophiolitic nappe toward the continental margin.

[68] The significance of pre-D1 ages at ~488 Ma recorded in metabasalts at amphibolite facies of the Shickshock Group and La Rédemption Complex (Figure 12) remains unclear. Hornblendes from both samples are chemically different than other analyzed hornblendes (magnesiohornblendes instead of tchermakitic) and they are not aligned within S1 foliation. The plateau age at 490.7 ± 4.4 Ma of sample 99Gasp192 could represent the crystallization age of hornblendes and as such the age of metabasalts. This would suggest that the youngest age of the Shickshock Group is close to the Cambrian-Ordovician boundary (Figure 4).

6.2. Late D1 Deformation, 459–456 Ma, Middle Taconian: Emplacement Onto the Continental Margin and Subsequent Propagation of Deformation

[69] Late D1 represents the first deformational event recorded by rocks of the continental Laurentian margin. It corresponds to the middle Taconian stage with the beginning of thrust stacking within the internal Humber zone (Mont Logan nappe and Lac Cascapédia window). This phase is characterized by retrograde metamorphism in the Amphibolite du Diable [*Pincivy et al.*, 2003], and prograde metamorphism with the development of an inverted metamorphic sequence in the Mont Logan Nappe [*Camiré*, 1995].

[70] Dated hornblende and muscovite crystals always underline the first metamorphic fabric S1 in each tectonometamorphic domain of the hinterland. On the other hand, the age of this fabric varies from the southeast to the northwest, ~459 Ma in the Amphibolite du Diable, down to ~457.5 in the southern part of the Mont Logan nappe at amphibolite metamorphic grade and ~456 Ma in the northern part of the Mont Logan nappe at greenschist metamorphic grade.

6.2.1. Ages of D1 in the Dunnage Zone

[71] Ages obtained on muscovites and amphiboles in the Amphibolite du Diable at ~459 Ma are highly concordant and suggest that cooling which led to the retrograde metamorphism was very rapid. This cooling was attributed to the uplift of the peridotite and of the metamorphic sole during their emplacement onto the continental margin [*Pincivy et al.*, 2003]. At ~459 Ma, the Mont Albert Complex and the Amphibolite du Diable were emplaced onto the more outboard part of the continental margin represented by basalt, arkose and conglomerate of the Shickshock Group (Figure 18b). It is suggested that the age at ~459 Ma is nearly the age of the end of deformation within the metamorphic soles of ophiolitic klippes.

6.2.2. Ages of D1 in the Internal Humber Zone

[72] Highly concordant ages at ~457.5 Ma displayed by amphiboles and muscovites underlying S1 from the amphibolite metamorphic facies of the Shickshock Group (Mont Logan nappe), as well as the age of a mica schist at the La Rédemption Complex, could suggest a rapid cooling. Therefore, it is proposed that the age at ~457.5 Ma represents the end of D1 deformation in the southern part of the Mont Logan nappe (Shickshock Group at amphibolite metamorphic grade).

[73] D1 deformation subsequently propagated northwestward within the Mont Logan nappe while temperature decreased and rocks of the Shickshock Group reached greenschist metamorphic conditions. The age at ~456 Ma yielded by muscovites of mica schists from the greenschist metamorphic facies is construed as a crystallization age close to the end of D1 deformation within the northern part of the Mont Logan nappe.

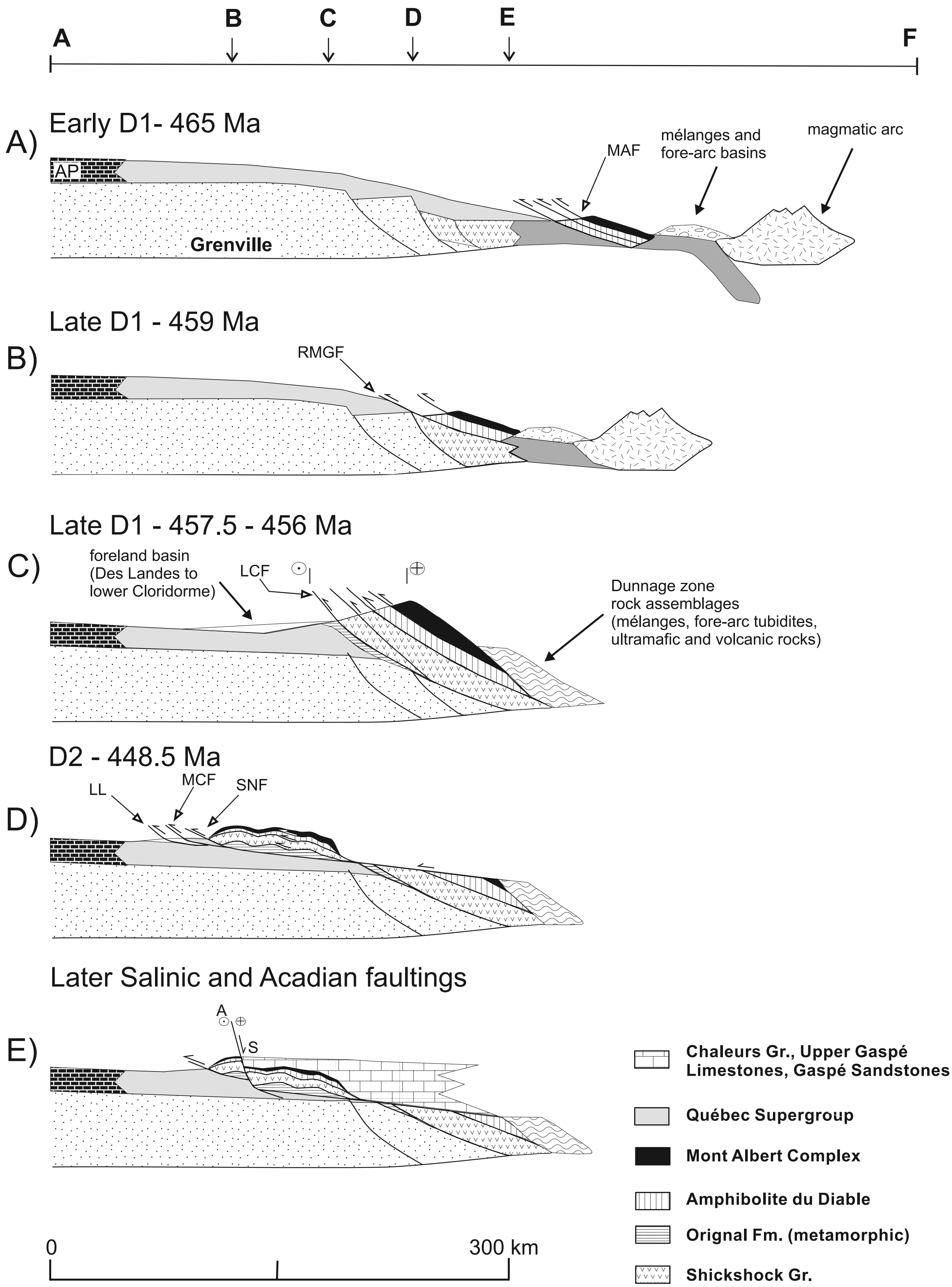
A
B
C
D
E
F
Early D1- 465 Ma
A)
AP
MAF
mélanges and
fore-arc basins
magmatic arc
Grenville
Late D1 - 459 Ma
B)
RMGF
Late D1 - 457.5 - 456 Ma
C)
foreland basin
(Des Landes to
lower Cloridorme)
LCF
Dunnage zone
rock assemblages
(mélanges, fore-arc tubidites,
ultramafic and volcanic rocks)
D2 - 448.5 Ma
D)
LL
MCF
SNF
Later Salinic and Acadian faultings
E)
A
S
Chaleurs Gr., Upper Gaspé
Limestones, Gaspé Sandstones
Québec Supergroup
Mont Albert Complex
Amphibolite du Diable
Orignal Fm. (metamorphic)
Shickshock Gr.
0
300 km

Figure 18

[74] Rocks of the Orignal Formation below the Mont Logan nappe within the Lac Cascapédia window were also affected by the late D1 deformation since they share the same D1-related structural features (see section 4.3, Figures 7 and 8). The Lac Cascapédia fault between the two tectonostratigraphic domains is considered as a synmetamorphic D1 fault which was subsequently folded by D2 (see below). We interpreted D1 within the Lac Cascapédia window as the expression of the overthrusting of rift-related rocks (basalt, arkose and conglomerate of the Shickshock Group) on distal rocks of the continental slope (mudslates of the Orignal Formation) (Figure 18c).

[75] Ages of late D1 indicate that deformation propagated northwestward during ~3 Ma (459 to 456 Ma) from the end of obduction (emplacement of the ophiolite onto the continental margin) to the overthrusting of the Mont Logan nappe onto the Rivière Sainte-Anne nappe (external Humber zone, Figures 1 and 4). This short period of time between the two "events" indicates that there is a close chronological link between the obduction of the Mont Albert Complex, late D1, and the development of an inverted metamorphic sequence in the Mont Logan Nappe [*Camiré*, 1995]. This suggests that the obduction was responsible for regional metamorphism in the internal Humber zone in the Gaspé Appalachians, as it was also suggested for the southern Quebec Appalachians [*Pinet and Tremblay*, 1995].

6.2.3. Ages of D1 in the External Humber Zone

[76] The ^{39}Ar-^{40}Ar ages determined in the internal Humber zone are in good agreement with the sedimentologic record within the external Humber zone. The Cap Chat Mélange is a tectonic and sedimentary mélange formed at the toe of advancing external nappes during late Llanvirnian to Caradocian times [*Cousineau*, 1998]. The filling of the synorogenic Caradocian flexural foreland basin is also an indication of tectonic activity to the south in the hinterland. Shales of the Des Landes Formation foredeep basin are followed by turbidites of the Cloridorme Formation [*Slivitzky et al.*, 1991; *Prave et al.*, 2001]. The Des Landes Formation contains graptolites from the *Nemagraptus gracilis* Zone (460.5 Ma to 457 Ma), whereas the Cloridorme Formation spans the *Climacograptus bicornis* to *Climacograptus spiniferus* Zones (457 Ma to 452 Ma) indicating, as a whole, a 460.5 Ma to 452 Ma time interval for deposition of both formations (Figure 4). The coarse part of turbidites contains rock fragments of sedimentary and volcanic rocks, and serpentinite, some of which containing chromite [*Enos*, 1969; *Hiscott*, 1978; *Slivitzky et al.*, 1991]. The nature of the Des Landes-Cloridorme basin and of rock fragments implies that: (1) the Laurentian crust was loaded at this time by an orogenic wedge to create the flexural foreland basin, and (2) the Mont Albert Complex and sedimentary rocks of the ancient passive margin (Rivière Sainte-Anne nappe) were part of the orogenic wedge which was eroding. The formation of this orogenic wedge is related to D1 which last from ~459 Ma to ~456 Ma in the internal Humber zone. D1 is not geochronologically dated in the external Humber zone of the Gaspé Peninsula, but Cambrian to Middle Ordovician rocks of the Quebec Supergroup (Figure 4) within the Rivière Sainte-Anne nappe were clearly involved in D1 deformation. The initiation of the Des Landes-Cloridorme foreland basin corresponds very well with the loading and thickening of the Laurentian margin to the south at ~459 Ma with ophiolite emplacement onto the margin (Figures 18b and 18c).

[77] The presence of chromite grains in greywacke of the Middle Ordovician Tourelle Formation (TO, Figure 4) implies that ophiolites started to be eroded before 459 Ma which is in agreement with the ~465 Ma age for intraoceanic thrusting of the Mont Albert Complex.

6.2.4. Geodynamic Setting of D1

[78] The nature of D1-related tectonic fabrics, as well as their attitude, varies from southeast to northwest. D1 is expressed by (1) a NE-trending mylonitic fabric S1, dipping moderately southeast, and accompanied by a downdip mineral lineation in the Amphibolite du Diable (Figures 6a and 6b); (2) a shallowly dipping NE-trending schistosity S1 (Figures 7a and 7c) accompanied by a mineral and stretching lineation L1 (Figures 7b, 7c, 7d, and 9), and isoclinal and recumbent F1 folds with axes parallel to the lineation (Figure 7a) in the internal Humber zone; and (3) NE-trending F1 folds with an axial-planar slaty cleavage S1 in the external Humber zone (Figures 10a and 10b). Kinematic indicators developed within the mylonitic fabric S1 in the Amphibolite du Diable [*Sacks et al.*, 2004], as well as a downdip elongation lineation L1, clearly indicate a northwestward structural transport of the peridotite during early D1 (Figure 18a). In the internal Humber zone, the NE-trending (orogen-parallel) elongation lineation L1, which usually indicates the line of transport [*Davis and Reynolds*, 1996], does not support, at first sight, northwestward structural transport of the Mont Logan nappe. This orogen-parallel lineation cannot be explained by a simple orthogonal thrusting model which had propagated northwestward after obduction. However, orogen-parallel extension is observed in many collisional orogens during prograde metamorphism in the early phase of deformation [*Ellis and Watkinson*, 1987]. Orogen-parallel stretching lineations have been described and attributed to oblique plate collision in the southern Appalachians [*Vauchez et al.*, 1993], the Variscan belt [*Brun and Burg*, 1982; *Burg et al.*, 1987], and the

Figure 18. Schematic tectonic evolution of the Humber and Dunnage zones in the Gaspé Peninsula. (a) Intraoceanic thrusting of the MAC during early D1. (b) Emplacement of the MAC and AD onto the external Laurentian margin, the Shickshock Group. (c) Northwest propagation of late D1 deformation. (d) Transport of nappes across the margin. (e) Synsedimentary extensional faulting followed by Acadian dextral strike-slip faulting along the Shickshock Sud fault. AD, Amphibolite du Diable; AP, Anticosti platform; MAC, Mont Albert Complex; MAF, Mont Albert fault; MCF, Méchins-Carcy fault; LCF, Lac Cascapédia fault; LL, Logan's Line; RMGF, Ruisseau des Marches du Géant fault; SNF, Shickshock Nord fault; SS, Shickshock Group.

Morocco Hercynian belt [*Lagarde and Michard*, 1985]. Collision in the Canadian Appalachians occurred along an irregular margin [*Stockmal et al.*, 1987, 1990] inherited from the opening of Iapetus ocean [*Thomas*, 1977]. In the Gaspé Appalachians of the Quebec reentrant, collision occurred along the paleotransform Canso fault [*Stockmal et al.*, 1990] which is a link between the Quebec reentrant and the St. Lawrence promontory (Figure 19a) [*Thomas*, 1977; *Malo and Kirkwood*, 1995; *Malo et al.*, 1995]. Direction of collision was probably controlled by the paleotransform fault and peri-Laurentian oceanic terranes slid northwestward and collided obliquely with the passive Laurentian margin and its Grenville basement (Figure 19b). Kinematic indicators and downdip stretching lineations along the Mont Albert fault within the mylonitized peridotite in the base of the Mont Albert Complex (hanging wall) and amphibolitic mylonites in slice 1 of the Amphibolite du Diable (footwall) reflect the intraoceanic thrusting, whereas similar shear features in slices 2 to 4 reflect structural transport toward northwest of ophiolite and imbrication of sedimentary and volcanic rocks in the oceanic domain before emplacement onto the margin (465 Ma to 459 Ma). Ordovician dextral shearing along the high-angle southeast dipping Shickshock Sud fault zone [*Sacks et al.*, 2004] and the orogen-parallel elongation lineation in the Mont Logan nappe were developed later during oblique collision (late D1 deformation; ~457.5 Ma in Shickshock Group rocks at amphibolite metamorphic facies and ~456 Ma in Shickshock Group rocks at greenschist facies, Figure 18c). The geometry of major thrusts and nappe stacking indicate an orthogonal structural transport in the external Humber zone (Figure 3). The global kinematics of late D1 deformation for the whole Humber zone is partitioned between oblique-slip thrusting (orogen-parallel) in the internal Humber zone and orogen-orthogonal thrusting in the external Humber zone. Coeval contractional structures and strike-slip faulting spatially separated may share the same displacement field and a common decollement system in collisional belt, and it is suggested that oblique convergence is the driving force for such systems [*Oldow et al.*, 1990].

6.3. D2 Deformation, ~448.5 Ma, Late Taconian: Structural Transport of Nappes on the Margin

[79] The D2 deformation recorded in rocks of Amphibolite du Diable, internal and external Humber zones is considered as the late stage of the Taconian orogeny (Figure 4).

6.3.1. Age of D2 in the Internal Humber Zone

[80] Several experiments yielded ages at ~448.5 Ma (e.g., one sample bearing two generations of amphibole, samples with only one generation of amphiboles, muscovites and amphiboles displaying disturbed age spectra). S1 foliation in the corresponding samples is usually folded and crenulated by D2 deformation. We propose that these ages at ~448.5 Ma characterize D2 which occurred at the same time throughout the Taconian hinterland (Figure 4) suggesting that rocks of the Amphibolite du Diable and of the Mont Logan nappe were already amalgamated during D2 metamorphic event which is supported by the fact that they share the same D2 deformation features, S2 crenulation cleavage (Figures 6d and 7b) and F2 folds (Figures 6a and 7a).

6.3.2. Age of D2 in the External Humber Zone

[81] There is no geochronological constraint on the age of D2 in the external Humber zone. The age of ~448.5 Ma, however, corresponds with the end of sedimentation in the foreland basin (parautochthonous zone, Figure 4). Youngest rocks of the Cloridorme Formation actually cropping out are upper Caradocian. We do not know, however, if younger foreland basin rocks are present under the St. Lawrence River further north (Figure 1). The N–NNW reverse folding in the Marsoui nappe and the parautochthonous zone (Figure 1) must postdate the foreland basin (post-Late Caradocian) and are related to the D2 deformation recorded in the internal Humber zone (Figure 4).

6.3.3. Geodynamic Setting of D2

[82] D2 deformation is expressed in the internal Humber zone by: (1) a SE-dipping S2 axial-planar to crenulation cleavage; upright to overturned, NE-trending folds that plunge SW or NE, and (2) folded syn-D1 faults such as the Lac Cascapédia fault (Figures 2, 3, and 18). In the external Humber zone, D2 is not well developed. The late S2 cleavage is only developed southward, close to the Shickshock Nord fault, which represents the internal-external boundary between metamorphic (greenschist grade) and nonmetamorphic rocks of the Humber zone. The Shickshock Nord fault is marked by a 5 to 10 m wide transition zone of alternating layers of gray mica schist and red-green slaty shale gently dipping to the NW.

[83] D1 deformation and related metamorphism occurred in response to obduction of a large ophiolitic nappe and overthrusting of the Mont Logan nappe (Lac Cascapédia fault) onto the Laurentian margin during the first oblique docking (Shickshock Sud fault) of oceanic terrains on the margin (Figure 18c). This crustal thickening occurred at the southern end of the continental margin, close to the southern limit of the Grenville basement where Shickshock Group rift-related basalts and strata where deposited. On the basis of deep seismic, gravity, and magnetic data in the Gulf of St. Lawrence [*Marillier et al.*, 1989; *Durling and Marillier*, 1990], geochemical and isotopic signatures of igneous rocks [*Ayuso and Bevier*, 1991; *Whalen*, 1993], and outcropping Grenville-like rocks in the Canadian Appalachians [*Hibbard et al.*, 2006], the actual southern limit of the Grenville basement is located under the Chaleurs Bay region (Figure 19a).

[84] An orogenic prism involving the more distal rocks of the Rivière Sainte-Anne nappe was formed at the end of D1 (~456 Ma) (Figure 18c). We propose that D2 is related to the structural transport of the Mont Logan nappe (more distal rocks of the early Paleozoic Laurentian margin) to their present-day position (Figure 19b). This transport occurred during the 456–448.5 time interval, and deposition of shales and turbidites in the foreland basin. This implies that S1 regional cleavage and F1 folds in the external Humber zone are probably in part contemporaneous with D2 in the internal Humber zone. Moreover, the Méchins-Carcy fault and eventually Logan's Line are D2-related thrusts. However, we do not know if they

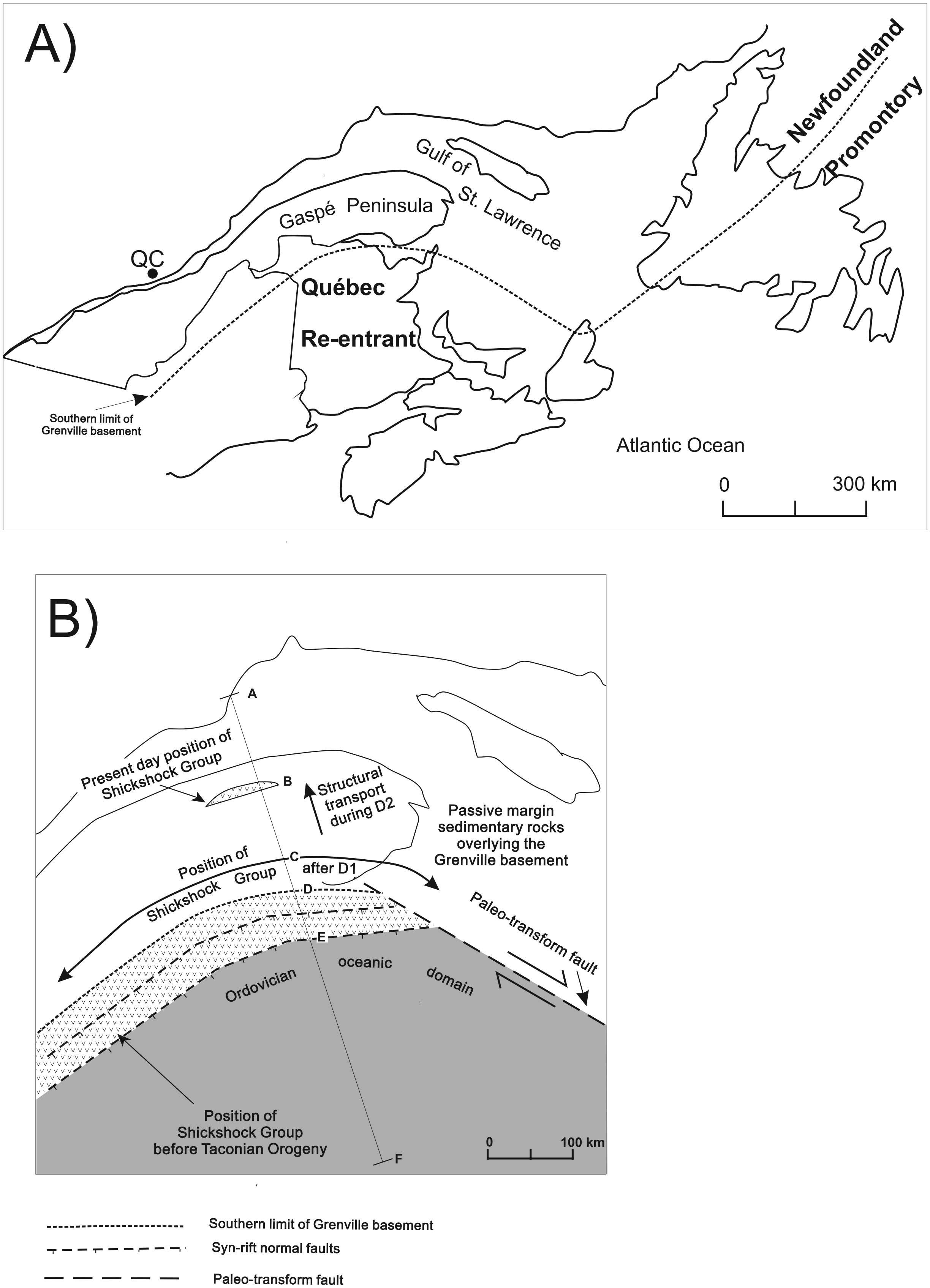
A)
Newfoundland
Promontory
Gulf of
St. Lawrence
Gaspé Peninsula
QC
Québec
Re-entrant
Southern limit of
Grenville basement
Atlantic Ocean
0
300 km
B)
A
Present day position of
Shickshock Group
B
Structural
transport
during D2
Passive margin
sedimentary rocks
overlying the
Grenville basement
Position of
Shickshock Group
C
after D1
D
E
Paleo-transform fault
Ordovician
oceanic
domain
Position of
Shickshock Group
before Taconian Orogeny
F
0
100 km
Southern limit of Grenville basement
Syn-rift normal faults
Paleo-transform fault

Figure 19

were reactivated by younger Salinic and/or Acadian deformation. The Mont Logan nappe was transported over a distance of approximately 150 km during ∼7.5 Ma. This represents a propagation rate of 2 cm/a.

[85] The driving force for D2 is related to the continued convergence of oceanic terrains of the Dunnage zone and tentatively associated with the collision of the Victoria-Popelogan arc of the Exploits subzone, peri-Gondwanan Iapetus oceanic terrains to the south [*van Staal*, 2005].

6.4. Younger Deformations of the Laurentian Margin

[86] One experiment on sericite from a mica schist of the amphibolite metamorphic facies of the Shickshock Group (99Gasp126) registered a disturbance of the K-Ar isotopic system that could be related to a deformational event younger than D2, the late stage of Taconian orogeny. The age at 446.5 ± 3.6 Ma is associated to D2, whereas the age at 417.8 ± 3.7 Ma corresponds to the Pridolian (Figure 4). The age of the Salinic unconformity recognized just south of the Shickshock Sud is Pridolian [*Bourque*, 2001]. This unconformity is related to synsedimentary normal block-faulting [*Bourque*, 2001; *Malo*, 2001]. Since the sample is at the contact with the Shickshock Sud fault, the younger age is tentatively correlated with this synsedimentary Salinic normal faulting (Figure 18e) and exhumation of metamorphic rocks of the Mont Logan nappe in the footwall of the fault.

7. Conclusion

[87] The new proposed structural model for the Taconian orogeny for the Humber and Dunnage zones in the Quebec reentrant of the Canadian Appalachians can be described in three stages (Figure 18).

[88] 1. Early D1, 465 to 459 Ma, corresponds to the intraoceanic thrusting processes and the structural transport of ophiolite in the Humber seaway oceanic domain. This is the early Taconian (Figure 18a).

[89] 2. Late D1, 459 Ma to 456 Ma, corresponds to the emplacement of ophiolite onto the continental margin and docking of the peri-Laurentian magmatic arc (e.g., Chain Lake-type terrain in the New England-Quebec Appalachians [*De Broucker*, 1987; *Boone and Boudette*, 1989], or the Dashwood block in Newfoundland Appalachian [*Waldron and van Staal*, 2001]). This is the middle Taconian (Figures 18b, 18c, and 19b).

[90] 3. D2, ∼448.5 Ma, corresponds to the structural transport of internal nappes across the margin and the collision further east of the Popelogan-Victoria arc [*van Staal*, 2005]. This is the late Taconian (Figure 18d and 19c).

[91] Two later phases of deformation have affected the Humber and Dunnage zones area after the Taconian orogeny. The Salinic disturbance during the Late Silurian-Early Devonian corresponds to an extensional phase (Figure 18e) and the Acadian orogeny occurring during post-Early Devonian and pre-Carboniferous time (Neoacadian [*van Staal*, 2005]) represents the last recorded shortening event; this latter deformation being responsible for late folding in the internal Humber zone [*Slivitzky et al.*, 1991].

[92] The influence of the margin geometry (promontories and reentrants) has been invoked for explaining the major transpressive deformation that occurred during the Acadian orogeny [*Malo et al.*, 1995]. Herein, it is interpreted to also have been a key factor during the Taconian orogeny. The position of the Gaspé Peninsula (Figure 19a), in the innermost part of the Quebec reentrant at the border with the ancient Canso transform fault, has created a geodynamical environment favorable for generation of young ophiolites such as the Mont Albert Complex, and for later development of strike-slip tectonics and transpression at the margin of the internal Humber zone. Other areas in the Canadian Appalachians (Figure 19), such as southern Quebec positioned in the reentrant and Newfoundland located along the promontory, have experienced different tectonic evolutions without major regional transpressive deformation. The southern Quebec Appalachians was submitted to Taconian thrust tectonics coeval with the obduction of a large ophiolitic nappe onto the Laurentian margin [*Pinet and Tremblay*, 1995; *Tremblay and Castonguay*, 2002; *Castonguay and Tremblay*, 2003]. This orogeny was followed, during the Silurian to early Devonian, by back thrusting and normal faulting attributed either to: (1) the tectonic wedging of a basement-cored duplex or (2) postorogenic extensional collapse of the internal Humber zone [*Castonguay et al.*, 2001; *Tremblay and Castonguay*, 2002; *Castonguay and Tremblay*, 2003; *Tremblay and Pinet*, 2005]. Finally, a last folding phase occurred during the Acadian orogeny in response to collision with Avalonia [*Pinet and Tremblay*, 1995]. In the Newfoundland Appalachians, thrusting and folding which occurred during the Taconian orogeny is interpreted as the product of the collision of the Dashwood microcontinent with the Laurentian margin [*Waldron and van Staal*, 2001]. Continental collision with Ganderia occurred during the Salinic orogeny and was followed by extensional collapse during the later stages of this orogeny [*Waldron et al.*, 1998]. Finally, compression continued in Newfoundland in response to accretion of Avalonia during the Acadian orogeny [*Cawood et al.*, 1995].

[93] In conclusion, we propose a new geodynamical model for the Taconian orogeny in which transpressive deformation was an important mode of deformation controlled by the particular position of the Gaspé Peninsula in the innermost part of the Quebec reentrant. The Appalachians of the Gaspé Peninsula could be a case study for understanding the tectonic evolution of a region located at the limit of a reentrant and a promontory along an irregular margin during an oceanic closure with obduction (Taconian orogeny) followed by a continental collision (Acadian orogeny).

Figure 19. (a) Position of the southern limit of Grenville in relation to Quebec reentrant/Newfoundland promontory pair in the Appalachians. (b) Map view of the Canadian Appalachians in the Quebec reentrant during D1 and D2.

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References

Alexandrov, P., G. Ruffet, and A. Cheilletz (2002), Muscovite recrystallisation and saddle-shaped ^{40}Ar/^{39}Ar age spectra: Example form the Blond granite (Massif Central, France), *Geochim. Cosmochim. Acta.*, *66*, 1793–1807, doi:10.1016/S0016-7037(01)00895-X.

Ayuso, R. A., and M. L. Bevier (1991), Regional differences in Pb isotopic compositions of feldspars in plutonic rocks of the northern Appalachian mountains, U.S.A., and Canada: A geochemical method of terrane correlation, *Tectonics*, *10*, 191–212, doi:10.1029/90TC02132.

Beaudin, J. (1980), Région du Mont-Albert et du Lac Matapédia, *DPV-705*, 50 pp., Min. of Energy and Resour., Quebec, Que., Canada.

Beaudin, J. (1984), Analyse structurale du Groupe des Shickshock et de la péridotite alpine du Mont Albert, Gaspésie, Ph.D. thesis, 241 pp., Univ. Laval, Quebec, Que., Canada.

Beausoleil, C., M. Malo, C. Morin, J. Y. Laliberté, and D. Brisebois (2002), Contrasting Taconian and Acadian structural styles along the new geophysical seismic reflection profiles in western Gaspé Appalachians, Matapedia Valley, paper presented at CSPG Annual Convention, Can. Soc. of Pet. Geol., Calgary, Alberta, Canada.

Bird, J. M., and J. F. Dewey (1970), Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen, *Geol. Soc. Am. Bull.*, *81*, 1031–1060, doi:10.1130/0016-7606(1970)81[1031:LPMTAT]2.0.CO;2.

Boone, G. M., and E. L. Boudette (1989), Accretion of the Boundary Mountains terrane within the northern Appalachian orthotectonic zone, in *Mélanges and Olistostromes of the U. S. Appalachians*, edited by H. W. Horton and N. Rast, *Spec. Pap. Geol. Soc. Am.*, *228*, 17–42.

Bourque, P. A. (2001), Sea-level, synsedimentary tectonics and reefs: Implication for hydrocarbon exploration in Silurian-lowermost Devonian Gaspé Belt, Québec Appalachians, *Bull. Can. Petrol. Geol.*, *49*, 217–237, doi:10.2113/49.2.217.

Brun, J. P., and J. P. Burg (1982), Combined thrusting and wrenching in the Ibero-Armorican arc: A corner effect during continental collision, *Earth Planet. Sci. Lett.*, *61*, 319–332, doi:10.1016/0012-821X(82)90063-2.

Burg, J. P., P. Bale, J. P. Brun, and J. Girardeau (1987), Stretching lineation and transport direction in the Ibero-Armorican arc during the Siluro-Devonian collision, *Geodin. Acta*, *1*, 71–87.

Camiré, G. (1995), Development of inverted metamorphic gradient in the internal domain of the Taconian belt, Gaspé Peninsula, *Can. J. Earth Sci.*, *32*, 37–51.

Camiré, G., M. Malo, and A. Tremblay (1993), Étude structurale et métamorphique des roches cambro-ordoviciennes du Groupe de Shickshock, Gaspésie, in *Current Research, Part D*, 93–1D, pp. 155–160, Geol. Surv. of Can., Ottawa.

Camiré, G., M. R. La Flèche, and G. A. Jenner (1995), Geochemistry of pre-Taconian mafic volcanism in the Humber Zone of the northern Appalachians, Québec, Canada, *Chem. Geol.*, *119*, 55–77, doi:10.1016/0009-2541(94)00104-G.

Castonguay, S., and A. Tremblay (2003), Tectonic evolution and significance of Silurian–Early Devonian hinterland-directed deformation in the internal Humber zone of the southern Quebec Appalachians, *Can. J. Earth Sci.*, *40*, 255–268, doi:10.1139/e02-045.

Castonguay, S., G. Ruffet, A. Tremblay, and G. Féraud (2001), Tectonometamorphic evolution of the southern Québec Appalachians: ^{40}Ar/^{39}Ar evidence for Middle Ordovician crustal thickening and Silurian/early Devonian exhumation of the internal Humber zone, *Geol. Soc. Am. Bull.*, *113*, 144–160, doi:10.1130/0016-7606(2001)113<0144:TEOTSQ>2.0.CO;2.

Cawood, P. A., and G. Suhr (1992), Generation and obduction of ophiolites: constraints from the Bay of Islands Complex, western Newfoundland, *Tectonics*, *11*, 884–897, doi:10.1029/92TC00471.

Cawood, P. A., J. A. M. van Gool, and G. R. Dunning (1995), Collisional tectonics along the Laurentian margin of the Newfoundland Appalachians, in *Current Perspectives in the Appalachians-Caledonian Orogen*, edited by J. P. Hibbard, C. R. van Staal, and P. A. Cawood, *Geol. Assoc. Can. Spec. Pap.*, *41*, 283–302.

Cheilletz, A., G. Ruffet, C. Marignac, O. Kolli, D. Gasquet, G. Féraud, and J. P. Bouillin (1999), ^{40}Ar/^{39}Ar dating of shear zones in the Variscan basement of Greater Kabylia (Algeria). Evidence of an Eo-Alpine event at 128 Ma (Hauterivian-Barremian boundary): Geodynamic consequences, *Tectonophysics*, *306*, 97–116, doi:10.1016/S0040-1951(99)00047-5.

Cousineau, P. A. (1998), Large-scale liquefaction and fluidization in the Cap-Chat Mélange, Québec Appalachians, *Can. J. Earth Sci.*, *35*, 1408–1422, doi:10.1139/cjes-35-12-1408.

Cox, R. A., and J. P. Hodych (2007), Ediacaran U-Pb zircon dates for the Lac Matapédia and Mt.-St. Anselme basalts of Quebec Appalachians: Support for a long-lived mantle plume during the rifting phase of Iapetus opening, *Can. J. Earth Sci.*, *44*, 564–581.

Davis, G. E., and S. J. Reynolds (1996), *Structural Geology of Rocks and Regions*, 2nd ed., 776 pp., John Wiley, Hoboken, N. J.

De Broucker, G. (1987), Stratigraphie, pétrographie et structure de la boutonnière de Maquereau - Mictaw (Région de Port-Daniel, Gaspésie), *MM 86–03*, 160 pp., Min. of Energy and Resour., Quebec, Que., Canada.

Durling, P. W., and F. J. Y. Marillier (1990), Structural trends and basement rock subdivisions in the western Gulf of St. Lawrence, northern Appalachians, *Atlantic Geol.*, *26*, 79–95.

Ellis, M., and A. J. Watkinson (1987), Orogen-parallel extension and oblique tectonics: The relation between stretching lineations and relative plate motions, *Geology*, *15*, 1022–1026, doi:10.1130/0091-7613(1987)15<1022:OEAOTT>2.0.CO;2.

Enos, P. (1969), Cloridorme Formation, Middle Ordovician flysch, northern Gaspé Peninsula, Québec, *Spec. Pap. Geol. Soc. Am.*, *117*, 66 pp.

Gagnon, Y. D., and R. A. Jamieson (1986), Étude de la semelle métamorphique du complexe du Mont Albert, Gaspésie, Québec, in *Current Research, Part B*, 86–1B, pp. 1–10, Geol. Surv. of Can., Ottawa.

Gray, D. R., R. T. Gregory, and J. M. L. Miller (2000), A new structural profile along the Muscat-Ibra transect, Oman: Implications for emplacement of the Samail ophiolite, in *Ophiolites and Oceanic Crust: New Insight From Field Studies and Ocean Drilling Program*, edited by Y. Dilek et al., *Spec. Pap. Geol. Soc. Am.*, *349*, 513–524.

Hesse, R., and E. Dalton (1991), Diagenetic and low-grade metamorphism terranes of the Gaspé Peninsula related to the geological structure of the Appalachians, *J. Metamorph. Geol.*, *9*, 775–790, doi:10.1111/j.1525-1314.1991.tb00565.x.

Hibbard, J. P., C. R. van Staal, D. W. Rankin, and H. Williams (2006), Lithotectonic map of the Appalachians Orogen, Canada-United States of America, *Map 2096A*, scale 1:1 500,000, Geol. Surv. of Canada, Ottawa.

Hiscott, R. N. (1978), Provenance of Ordovician deep-water sandstone, Tourelle Formation, Québec, and implications for initiation of the Taconic Orogeny, *Can. J. Earth Sci.*, *15*, 1579–1597.

Islam, S., R. Hesse, and A. Chagnon (1982), Zonation of diagenesis and low-grade metamorphism in Cambro-Ordovician flysch of Gaspé Peninsula Quebec Appalachians, *Can. Min.*, *20*, 155–167.

Kirkwood, D. (1999), A palinspastic restoration of a post-Taconian sucessor basin deformed within a transpressive setting, northern Appalachians, *Tectonics*, *18*, 1027–1040, doi:10.1029/1999TC900039.

Kirkwood, D., M. Lavoie, and J. S. Marcil (2004), Structural style and hydrocarbon potential in the Acadian foreland thrust and fold belt, Gaspé Appalachians, Canada, in *Deformation, Fluid Flow, and Reservoir Appraisal in Foreland Fold and Thrust Belts*, *Hedberg Ser.*, vol. 1, edited by R. Swennen, F. Roure, and J. W. Granath, pp. 412–430, Am. Assoc. of Pet. Geol., Tulsa, Okla.

Lagarde, J. L., and A. Michard (1985), Stretching normal to the regional thrust displacement in a thrust-wrench shear zone, Rehamna Massif, Morocco, *J. Struct. Geol.*, *3/4*, 483–492.

Leake, B. E. (1978), Nomenclature of amphiboles, *Can. Min.*, *16*, 501–520.

Lux, D. R. (1986), ^{40}Ar/^{39}Ar ages for minerals from the amphibolite dynamothermal aureole, Mont Albert, Gaspé, Quebec, *Can. J. Earth Sci.*, *23*, 21–26.

Malo, M. (2001), Late Silurian-Early Devonian tectono-sedimentary history of the Gaspé Belt in the Gaspé Peninsula: From a transtensional Salinic basin to an Acadian foreland basin, *Bull. Can. Petrol. Geol.*, *49*, 202–216, doi:10.2113/49.2.202.

Malo, M., and J. Béland (1989), Acadian strike-slip tectonics in the Gaspé region, Québec Appalachians, *Can. J. Earth Sci.*, *26*, 1764–1777.

Malo, M., and D. Kirkwood (1995), Faulting and progressive strain history of the Gaspé Peninsula in post-Taconian time: A review, in *Current Perspectives in the Appalachian-Caledonian Orogen*, edited by J. P. Hibbard, C. R. van Staal, and P. A. Cawood, *Geol. Assoc. Can. Spec. Pap.*, *41*, 267–282.

Malo, M., D. Kirkwood, G. De Broucker, and P. St-Julien (1992), A reevaluation of the position of the Baie Verte-Brompton Line in the Québec Appalachians: the influence of Middle Devonian strike-slip faulting in Gaspé Peninsula, *Can. J. Earth Sci.*, *29*, 1265–1273.

Malo, M., A. Tremblay, D. Kirkwood, and P. Cousineau (1995), Along-strike structural variations in the

Quebec Appalachians: Consequence of a collision along an irregular margin, *Tectonics*, *14*, 1327–1338, doi:10.1029/95TC01449.

Malo, M., P. A. Cousineau, P. E. Sacks, J. F. W. Riva, E. Asselin, and P. Gosselin (2001), Age and composition of the Ruisseau Isabelle Mélange along the Shickshock Sud fault zone: Constraints on the timing of mélanges formation in the Gaspé Peninsula, *Can. J. Earth Sci.*, *38*, 21–42, doi:10.1139/cjes-38-1-21.

Marillier, F., C. E. Keen, G. Stockmal, G. Quinlan, H. Williams, and S. J. O'Brien (1989), Crustal structures and surface zonation of the Canadian Appalachians: Implications of deep seismic reflection data, *Can. J. Earth Sci.*, *26*, 305–321.

Mattinson, C. R. (1964), Mount Logan area, Gaspé Peninsula, *Geol. Rep. 118*, 102 pp., Dep. of Nat. Resour., Quebec, Que., Canada.

O'Beirne-Ryan, A. M., R. A. Jamieson, and Y. D. Gagnon (1990), Petrology of garnet-clinopyroxene amphibolites from Mont Albert, Gaspé, Quebec, *Can. J. Earth Sci.*, *27*, 72–86.

Oldow, J. S., A. W. Bally, and H. G. A. Lallemant (1990), Transpression, orogenic float, and lithospheric balance, *Geology*, *18*, 991–994.

Pincivy, A. (2003), Géochronologie 40Ar/39Ar et analyse structurale de la zone de Humber des Appalaches de Gaspésie (Québec, Canada): Implications sur la tectonique des Appalaches du nord, Ph.D. thesis, 285 pp., Univ. Québec, INRS, Quebec, Que., Canada, and Univ. Rennes 1, Rennes, France.

Pincivy, A., M. Malo, G. Ruffet, A. Tremblay, and P. Sacks (2003), Regional metamorphism of the Appalachian Humber zone of Gaspé Peninsula: ^{40}Ar/^{39}Ar evidence for crustal thickening during the Taconian orogeny, *Can. J. Earth Sci.*, *40*, 301–315, doi:10.1139/e02-076.

Pinet, N., and A. Tremblay (1995), Tectonic evolution of the Québec-Maine Appalachians: From oceanic spreading to obduction and collision in the northern Appalachian, *Am. J. Sci.*, *295*, 173–200.

Prave, A. R., L. G. Kessler II, M. Malo, W. V. Bloechl, and J. Riva (2001), Ordovician foredeep evolution and arc collision, Québec: The Taconic orogeny in Canada and its bearing on the Grampian Orogeny in Scotland, *J. Geol. Soc.*, *157*, 393–400.

Roddick, J. C. (1983), High precision intercalibration of ^{40}Ar/^{39}Ar standards, *Geochim. Cosmochim. Acta.*, *47*, 887–898, doi:10.1016/0016-7037(83)90154-0.

Ruffet, G., H. Perroud, and G. Feraud (1990), ^{40}Ar-^{39}Ar dating of a late Proterozoic paleomagnetic pole for the Armorican Massif (France), *Geophys. J. Int.*, *102*, 397–409, doi:10.1111/j.1365-246X.1990.tb04473.x.

Ruffet, G., G. Féraud, and M. Amouric (1991), Comparison of ^{40}Ar/^{39}Ar conventional and laser dating of biotites from the North Trégor Batholith, *Geochim. Cosmochim. Acta.*, *55*, 1675–1688, doi:10.1016/0016-7037(91)90138-U.

Ruffet, G., G. Féraud, M. Ballèvre, and J. R. Kiénast (1995), Plateau ages and excess argon on phengites: A ^{40}Ar/^{39}Ar laser probe study of alpine micas (Sesia zone), *Chem. Geol.*, *121*, 327–343, doi:10.1016/0009-2541(94)00132-R.

Sacks, P., M. Malo, W. E. Trzcienski Jr., A. Pincivy, and P. Gosselin (2004), Taconian and Acadian transpression between the internal Humber Zone and the Gaspé Belt in the Gaspé Peninsula: Tectonic history of the Shickshock Sud fault zone, *Can. J. Earth Sci.*, *41*, 635–653, doi:10.1139/e04-018.

Schroetter, J. M., P. Pagé, J. H. Bédard, A. Tremblay, and V. Bécu (2003), Forearc extension an seafloor spreading in the Theford Mines Ophiolite Complex, in *Ophiolites Earth History*, edited by Y. Dilek and P. T. Robinson, *Geol. Soc. Spec. Publ.*, *218*, 231–251.

Slivitzky, A., P. St-Julien, and G. Lachambre (1991), Synthèse géologique du Cambro-Ordovicien du Nord de la Gaspésie, *ET 88–14*, 61 pp., Min. of Energy and Resour., Quebec, Que., Canada.

St-Julien, P., and C. Hubert (1975), Evolution of the Taconian Orogen in the Québec Appalachians, *Am. J. Sci.*, *275*, 337–362.

St-Julien, P., W. E. Trzcienski Jr., and C. Wilson (1990), A structural, petrological and geochemical traverse of the Shickshock Terrane, Gaspésie, in *Guidebook for Field Trip in Gaspésie*, edited by W. E. Trzcienski Jr., pp. 248–285, New England Intercollegiate Geol. Conf., Montreal Univ., Montreal, Quebec, Canada.

Stockmal, G. S., S. P. Colmann-Sadd, C. E. Keen, S. J. O'Brien, and G. Quinlan (1987), Collision along an irregular margin: A regional plate tectonic interpretation for the Canadian Appalachians, *Can. J. Earth Sci.*, *24*, 1098–1107.

Stockmal, G. S., S. P. Colmann-Sadd, C. E. Keen, F. Marillier, S. J. O'Brien, and G. Quinlan (1990), Deep seismic structure and plate tectonic evolution of the Canadian Appalachians, *Tectonics*, *9*, 45–61, doi:10.1029/TC009i001p00045.

Thomas, W. A. (1977), Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin, *Am. J. Sci.*, *277*, 1233–1278.

Tremblay, A., and S. Castonguay (2002), Structural evolution of the Laurentian margin revisited (southern Québec Appalachians): Implications for the Salinian orogeny and successor basins, *Geology*, *30*, 79–82.

Tremblay, A., and N. Pinet (2005), Silurian to Early Devonian tectonic evolution of the Northern Appalachians (Canada and northeastern USA) and the origin the Connecticut Valley-Gaspé and Merrimack throughs, *Geol. Mag.*, *142*, 7–22.

Tremblay, A., G. Ruffet, and S. Castonguay (2000), Acadian metamorphism in the Dunnage zone of the southern Québec Appalachians: ^{40}Ar/^{39}Ar evidence for collision diachronism, *Geol. Soc. Am. Bull.*, *112*, 136–146, doi:10.1130/0016-7606(2000)112<0136:AMITDZ>2.3.CO;2.

Tucker, R. D., T. E. Krogh, R. J. Ross Jr., and S. H. Williams (1990), Time-scale calibration by high-precision U-Pb zircon dating of interstratified volcanic ashes in the Ordovician and Lower Silurian stratotypes of Britain, *Earth Planet. Sci. Lett.*, *100*, 51–58, doi:10.1016/0012-821X(90)90175-W.

Turner, G., J. C. Huneke, F. A. Podosek, and G. J. Wasserburg (1971), ^{40}Ar/^{39}Ar ages and cosmic ray exposure age of Apollo 14 samples, *Earth Planet. Sci. Lett.*, *12*, 19–35, doi:10.1016/0012-821X(71)90051-3.

van Staal, C. R. (2005), The northern Appalachians, in *Encyclopedia of Geology*, vol. 4, edited by R. C. Selley et al., pp. 81–91, Elsevier, New York.

van Staal, C. R., J. F. Dewey, C. Mac Niocaill, and W. S. McKerrow (1998), The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: History of a complex west and southwest Pacific-type segment of Iapetus, in *Lyell: The Past is the Key to the Present*, edited by D. J. Blundell and A. C. Scott, *Geol. Soc. Spec. Publ.*, *143*, 199–242.

Vauchez, A., H. A. Babaie, and A. Babaie (1993), Orogen-parallel tangential motion in the Late Devonian-Early Carboniferous southern Appalachian internides, *Can. J. Earth Sci.*, *30*, 1297–1305.

Waldron, J. W. F., and C. R. van Staal (2001), Taconic Orogeny and the accretion of the Dashwoods block: A peri-Laurentian microcontinent in the Iapetus Ocean, *Geology*, *29*, 811–814, doi:10.1130/0091-7613(2001)029<0811:TOATAO>2.0.CO;2.

Waldron, J. W. F., S. D. Anderson, P. A. Cawood, L. B. Goodwin, J. Hall, R. A. Jamieson, S. E. Palmer, G. R. Stockmal, and P. F. Williams (1998), Evolution of the Appalachian Laurentian margin: Lithoprobe results in western Newfoundland, *Can. J. Earth Sci.*, *35*, 1271–1287, doi:10.1139/cjes-35-11-1271.

Webby, B. D., R. A. Cooper, S. M. Bergström, and F. Paris (2004), Stratigraphic framework and time slices, in *The Great Ordovician Biodiversity Event*, edited by B. D. Webby et al., pp. 41–47, Columbia Univ. Press, New York.

West, D. P., Jr., and D. R. Lux (1993), Dating mylonitic deformation by the ^{40}Ar/^{39}Ar method: An example form the Norumbega Fault Zone, Maine, *Earth Planet. Sci. Lett.*, *120*, 221–237, doi:10.1016/0012-821X(93)90241-Z.

Whalen, J. B. (1993), Geology, petrography, and geochemistry of Appalachians granites in New Brunswick and Gaspésie, Québec, *Bull. Geol. Surv. Can.*, *436*, 124 pp..

Williams, H. (1979), Appalachian Orogen in Canada, *Can. J. Earth Sci.*, *16*, 792–807.

Williams, H. (1995), Temporal and spatial divisions, in *Geology of the Appalachian/Caledonian Orogen in Canada and Greenland*, *Geol. Can.*, vol. 6, edited by H. Williams, pp. 21–44, Geol. Surv. of Can., Ottawa.

Williams, H., and P. St-Julien (1982), The Baie Verte-Brompton Line: Early Paleozoic continent ocean interface in the Canadian Appalachians, in *Major Structural Zones and Faults of the Northern Appalachians*, edited by P. St-Julien and J. Béland, *Geol. Assoc. Can. Spec. Pap.*, *24*, 177–208.

Williams, H., K. L. Currie, and H. S. Swinden (1988), Tectonostratigraphic subdivisions of central Newfoundland, in *Current Research, Part B*, 88–1B, pp. 91–98, Geol. Surv. of Can., Ottawa.

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